THESIS

ENSEMBLE-BASED ANALYSIS OF FRONT RANGE SEVERE CONVECTION ON 6-7 JUNE 2012: FORECAST UNCERTAINTY AND COMMUNICATION OF WEATHER INFORMATION TO FRONT RANGE DECISION-MAKERS

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ABSTRACT

ENSEMBLE-BASED ANALYSIS OF FRONT RANGE SEVERE CONVECTION ON 6-7 JUNE 2012: FORECAST UNCERTAINTY AND COMMUNICATION OF WEATHER INFORMATION TO FRONT RANGE DECISION-MAKERS

The variation of topography in Colorado not only adds to the beauty of its landscape, but also tests our ability to predict warm season severe convection. Deficient radar coverage and limited observations make quantitative precipitation forecasting quite a challenge. Past studies have suggested that greater forecast skill of mesoscale convection initiation and precipitation characteristics are achievable considering an ensemble with explicitly predicted convection compared to one that has parameterized convection. The range of uncertainty and probabilities in these forecasts can help forecasters in their precipitation predictions and communication of weather information to emergency managers (EMs). EMs serve an integral role in informing and protecting communities in anticipation of hazardous weather.

An example of such an event occurred on the evening of 6 June 2012, where areas to the lee of the Rocky Mountain Front Range were impacted by flash-flood-producing severe convection that included heavy rain and copious amounts of hail. Despite the discrepancy in the timing, location and evolution of convection, the convection-allowing ensemble forecasts generally outperformed those of the convection-parameterized ensemble in representing the mesoscale processes responsible for the 6-7 June severe convective event. Key features sufficiently reproduced by several of the convection-allowing ensemble members resembled the observations: 1) general location of a convergence boundary east of Denver, 2) convective

initiation along the boundary, 3) general location of a weak cold front near the Wyoming/Nebraska border, and 4) cold pools and moist upslope characteristics that contributed to the backbuilding of convection. Members from the convection-parameterized ensemble that failed to reproduce these results displaced the convergence boundary, produced a cold front that moved southeast too quickly, and used the cold front for convective initiation. The convection-allowing ensemble also showed greater skill in forecasting heavy precipitation amounts in the vicinity of where they were observed during the most active convective period, particularly near urbanized areas.

A total of 9 Front Range EMs were interviewed to research how they understood hazardous weather information, and how their perception of forecast uncertainty would influence their decision making following a heavy rain event. Many of the EMs use situational awareness and past experiences with major weather events to guide their emergency planning. They also highly valued their relationship with the National Weather Service to improve their understanding of weather forecasts and ask questions about the uncertainties. Most of the EMs perceived forecast uncertainty in terms of probability and with the understanding that forecasting the weather is an imprecise science. The greater the likelihood of occurrence (implied by a higher probability of precipitation) showed greater confidence in the forecast that an event was likely to happen. Five probabilistic forecast products were generated from the convection-allowing ensemble output to generate a hypothetical warm season heavy rain event scenario. Responses varied between the EMs in which products they found most practical or least useful. Most EMs believed that there was a high probability for flooding, as illustrated by the degree of forecasted precipitation intensity. Most confirmed perceiving uncertainty in the different forecast representations, sharing the idea that there is an inherent uncertainty that follows modeled forecasts. The long-term goal of this research is to develop and add reliable probabilistic forecast products to the “toolbox” of decision-makers to help them better assess hazardous weather information and improve warning notifications and response.

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Global Forecast System forecast data were provided by the National Climatic Data Center's National Operational Model Archive & Distribution System (NCDC NOMADS). Precipitation analyses were obtained from the regional 6 hourly multi-sensor precipitation analyses generated by the 12 River Forecast Centers. Archived surface analyses and Denver, Colorado Skew-T-logp soundings was retrieved from the Storm Prediction Center (SPC). The Fort Morgan, Colorado Skew-T-logp sounding was obtained from the Deep Convective Clouds and Chemistry (DC3) Experiment. Radar reflectivity data were gathered from the NCDC NEXRAD Data Inventory database. Surface observational data was obtained from the Iowa State GEMPAK archive. Satellite imagery was requested from Dr. Dan Lindsey (CIRA). The MODE tool is developed by the Developmental Testbed Center (DTC).

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CHAPTER 1

INTRODUCTION

1.1 Hazards of flash floods

Among all weather related disasters (tornadoes, hurricanes, heat waves, etc.) that occur in the United States, floods are the deadliest hazard associated with convection (Olson et al. 1995). Furthermore, most of the flood related fatalities are attributed to flash flood events (Ashley and Ashley 2008). According to a preliminary statistical study compiled by the National Weather Service (NWS) Office of Climate, Water, and Weather Services and the National Climatic Data Center (NCDC) for 2012, floods (including flash and river floods) have accounted for an average of 89 fatalities per year over a 30 year period (1983-2012) (Fig. 1.1). Flash flooding not only can produce significant loss of life, but also substantial economic impacts. In the year 2012 alone, flash floods were responsible for over $376M dollars in property and crop damage. Although tornado-related casualties have steadily decreased since the 1950s owing to the improvements made in forecasting, warning notifications, and public preparedness, unfortunately the same cannot be said of flash flood related casualties (Doswell et al. 1996).

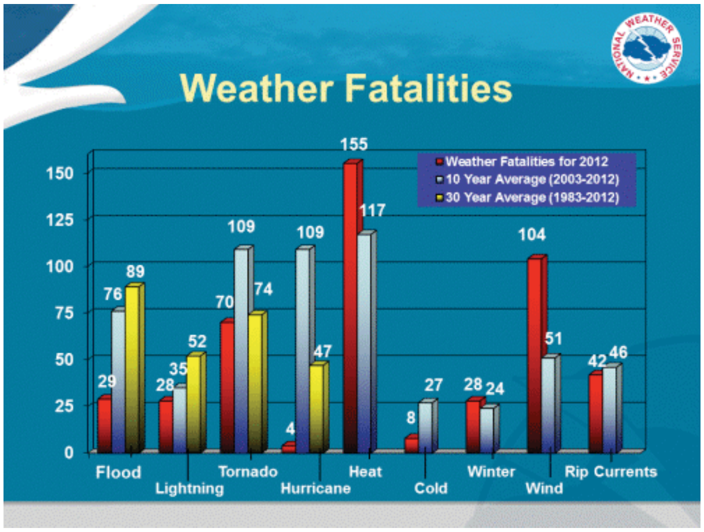


Fig.1.1: The United States preliminary 2012 Natural Hazards Statistics. (Source: http://www.nws.noaa.gov/om/hazstats.shtml).

1.2 Motivation for improving flash flood forecasting

Ashley and Ashley (2008) compiled a nationwide database of flood fatalities for the United States from 1959 to 2005, which showed that four out of the five years of high flood fatalities occurred in the 1970s (Fig. 1.2). For example, 237 of the fatalities in 1972 were as a result of heavy rainfall and a dam failure that led to a flash flood event in the downtown area of Rapid City, South Dakota (Maddox et al. 1978, Carter et al. 2002). In 1976, the Big Thompson Canyon flash flood was responsible for 156 fatalities due to a stationary orographically-induced thunderstorm near the top of the canyon (Henz et al. 1976, Maddox et al. 1977, Caracena et al. 1979). The year 1977 was characterized by several high-fatality events, one of which was the heavy rains and failing dams that killed 74 people in Cambria County, Pennsylvania (Bosart and Sanders 1981). These deadly flash flood events in the 1970s underline several situations in which the risk for a flash flood is likely. These include heavy precipitation falling over an urbanized area, over rugged topography with narrow canyons, or falling over an area that is additionally suffering from failing structures that are purposely designed to retain water.

Therefore, the meteorology, geography, hydrology, and urbanization all play a role in creating a variety of circumstances that may act to augment the impacts of heavy precipitation over a given area. Consequently, the flash flood events of the 1970s had generated an impetus in the meteorological research community towards improving and producing effective flash flood forecasts.

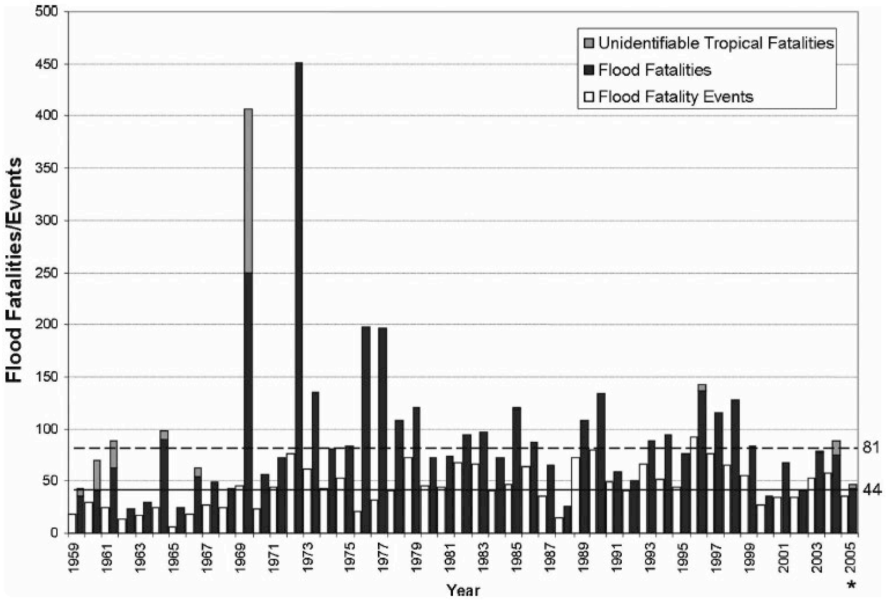


Fig. 1.2: The frequency of flood fatalities and fatality events (excluding indirect) from 1959 to 2005. Black bars represent deaths due strictly to flooding for all event types in the study of Ashley and Ashley (2008). Gray bars represent death due to tropical systems but not to flooding alone. Light gray bars represent deadly events. The dashed horizontal line represents yearly fatality median, and the nondashed horizontal line represents yearly fatality event median. The asterisk indicates that 2005 data are preliminary and do not include Hurricane Katrina fatalities from Louisiana. From Ashley and Ashley (2008).

One of the first steps made in the effort to progress flash flood forecasting was to investigate the meteorological conditions most commonly associated with precipitation systems conducive for extreme rainfall and, ultimately, flooding. Work conducted by Maddox et al. (1979) served as one of the first pioneering pieces of research that examined the synoptic and mesoscale characteristics of 151 heavy precipitation events across the United States from 1973-

1977. These events were categorized into four distinct patterns that described the general surface and upper-air features in which they typically developed in, namely 1) synoptic, 2) frontal, 3) mesohigh, and 4) western. Herein, the synoptic, frontal, and mesohigh events will not be discussed, as the event being considered in this research work takes place in the western United States. Western events were considered to be all flash flood events that had affected areas of the United States west of 104° longitude.

The western events identified by Maddox et al. (1979) were characterized by a late afternoon or early evening onset for heavy precipitation, which would logically parallel maximum atmospheric destabilization periods (Fig. 1.3a). This is compared to the nocturnal nature of those events in the eastern half of the United States. Furthermore, the flash flood events not only differed in the timing of precipitation but also in the quantity; the maximum precipitation amounts for those in east (west) were typically associated with rainfall amounts greater (less) than four inches (Fig. 1.3b). Out of the 151 flash flood events studied, 31 were classified as western events. Most of these western flash floods occurred beneath weak large scale patterns and without distinct surface characteristics. It was suggested that frontal boundaries, outflow from thunderstorms, or topographic features interacted with large scale features to generate local heavy rainfall; no surface or upper air composite maps were generated due to the small sample of western events.

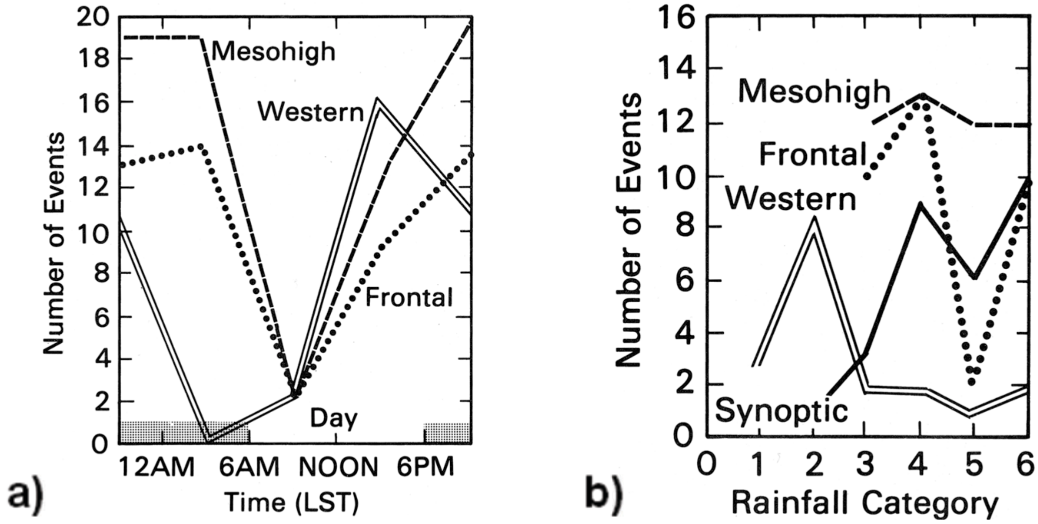


Fig. 1.3: (a) The timing of the onset of heavy rains for three types of flash flood events. The number of events that began in each 6-hour interval is plotted at the midpoint of the interval. (b) Maximum precipitation amounts reported for flash flood events. The rainfall categories are: 1) <2 inches; 2) 2 to <4 inches; 3) 4 to <6 inches, 4) 6 to <8 inches; 5) 8 to <10 inches; and 6) ≥10 inches. From Maddox et al. (1979).

Unfortunately, not much research has been dedicated towards understanding the meteorological characteristics specifically for flash flood events that take place in the western United States. The past research that has been done (and will be discussed herein) serves as valuable sources of information that is of particular significance in this thesis work. Motivated by the lack of meteorological composite charts and inadequate sample size, an extended study by Maddox et al. (1980) was conducted to focus solely on flash flood events that occurred in the western United States. The challenges in quantitative precipitation forecasting for the west were well acknowledged, as the study mentioned factors such as rapid precipitation runoff, deficient radar coverage, and limited observations due to sparse populations and rugged terrain. As these impediments make it difficult to identify important surface features, the 61 western flash flood events studied were categorized by similar 500 hPa upper air flow patterns resulting in four distinguishing types: Type I, Type II, Type III, and Type IV.

A majority of the western flash flood events studied by Maddox et al. (1980) were classified as Type I events (29 out of 61), which were associated with a weak 500 hPa short wave that was moving upstream of an upper level ridge (Fig. 1.4a). Flash flooding was likely to occur in the area ahead of the short wave where instability and moisture values were maximized. Additionally, a weak surface front under the ridge acted to focus the convective activity. Type II events, characterizing 12 out of 61 western flash flood events, were just opposite of Type I in that they were associated with a 500 hPa short wave moving downstream of an upper level ridge (Fig. 1.4b). Yet, the area susceptible to flash flooding was similar to that found in Type I.

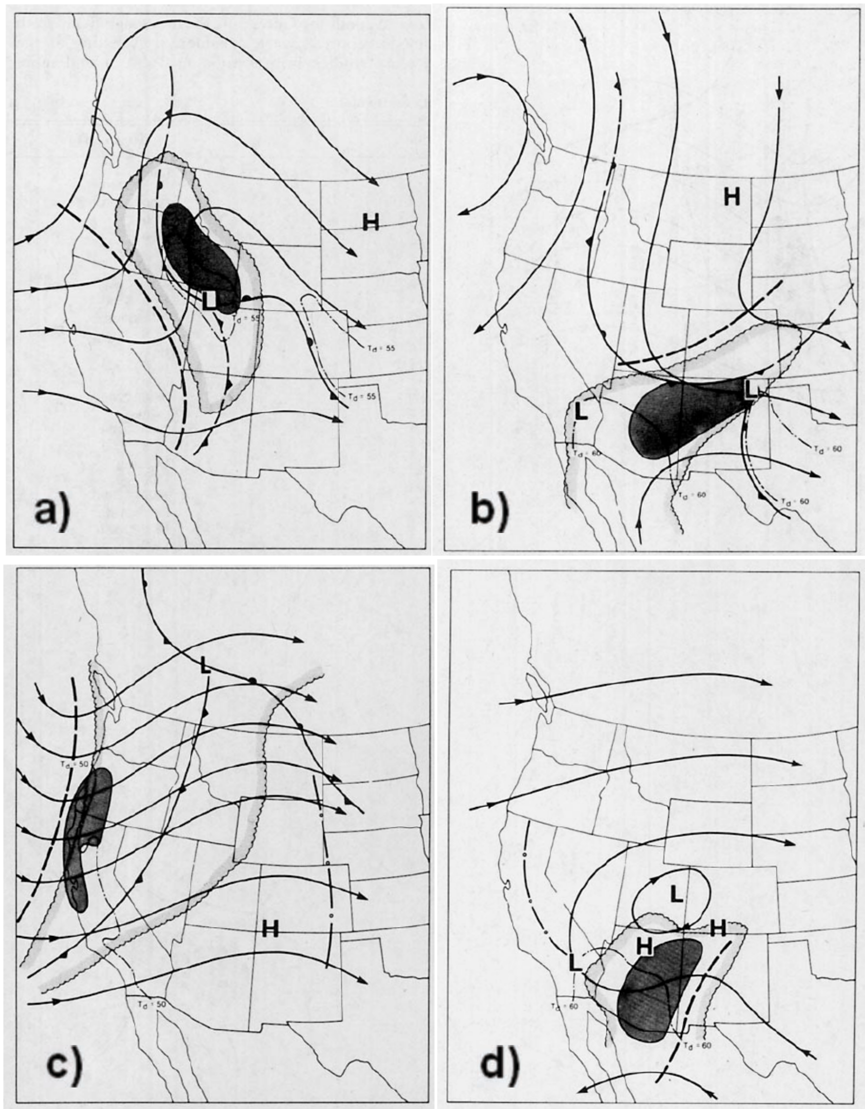


Fig. 1.4: (a) Generalized 500 hPa and surface patterns for Type I western flash floods. Streamlines for 500 hPa flow are shown and 500 hPa trough position is depicted as a heavy dashed line. Region at 500 hPa with $T\text{-}T_d \leq 6°C$ is outlined. Surface fronts and pressure centers are indicated, as well as isopleths for regions with high surface dewpoint temperatures. Time of analysis is just prior (0-3 h) to onset of storm activity. Region with potential for heavy precipitation is shaded. (b) Generalized 500 hPa and surface patterns for Type II western flash floods; details are similar to those in Fig. 1.4(a). (c) Generalized 500 hPa and surface patterns for Type III western flash floods; details are similar to Fig. 1.4(a) except that time of analysis is near the end of the heavy precipitation event. (d) Generalized 500 hPa and surface patterns for Type IV western flash floods; details are similar to those in Fig. 1.4(a). From Maddox et al. (1980).

Strong synoptic systems distinguished 12 out of 61 western flash flood events, designated as Type III events. In these events, flash flooding was likely in areas where strong, moist low level flow interacted with mountainous terrain leading to the development of embedded thunderstorms capable of producing localized heavy rainfall (Fig. 1.4c). The last 8 out of 61 western flash flood events were associated with weak 500 hPa short wave troughs moving through easterly or westerly zonal flow, classifying the Type IV events. Compared to the events in Type I and II, the short wave features in the Type IV events were positioned north or south of an upper level ridge that was orientated east to west (Fig. 1.4d). More than half of the events studied by Maddox et al. (1980) had reports of severe thunderstorms. The distribution in the onset of heavy rainfall for Type I, II, and IV western flash flood events was similar to that of Maddox et al. (1979), as well as the distribution in precipitation amounts. Furthermore, the western flash flood events had a tendency to be short-lived yet intense thunderstorms that generated 2 to 4 inches of precipitation.

The geographical and monthly distribution of the western flash flood event types was also explored by Maddox et al. (1980). Much of the region in between the Sierra Mountain ranges and the Continental Divide were impacted by Type I events (Fig. 1.5a), most of which occurred during the summer months (Fig. 1.5b). Type II events mainly occurred over the southeast portion of the domain of interest, and during the second half of summer and into early fall. It is apparent that Type III events dominated the Pacific Coast, and during the winter months. Lastly, the desert southwest was the main target for Type IV events, and commonly took place during July. Looking deeper into the geographical distribution of western flash flood events, it is interesting to note that there is a cluster of diverse event types confined to the Front Range of the Rocky Mountains in Colorado. This particular area of interest is also distinguished not only by its dense population but also the change in landscape from mountainous terrain to flat plains. Such a unique terrain interface results in a combination of severe convection similar to that found in the Great Plains of the United States, and terrain-influenced severe convection. As previously mentioned, severe thunderstorm activity was reported with more than 50% of the western flash flood events studied by Maddox et al. (1980). Therefore, it is important to study the environmental conditions conducive for severe convective weather in the High Plains; one such study that proposed this objective was Doswell (1980).

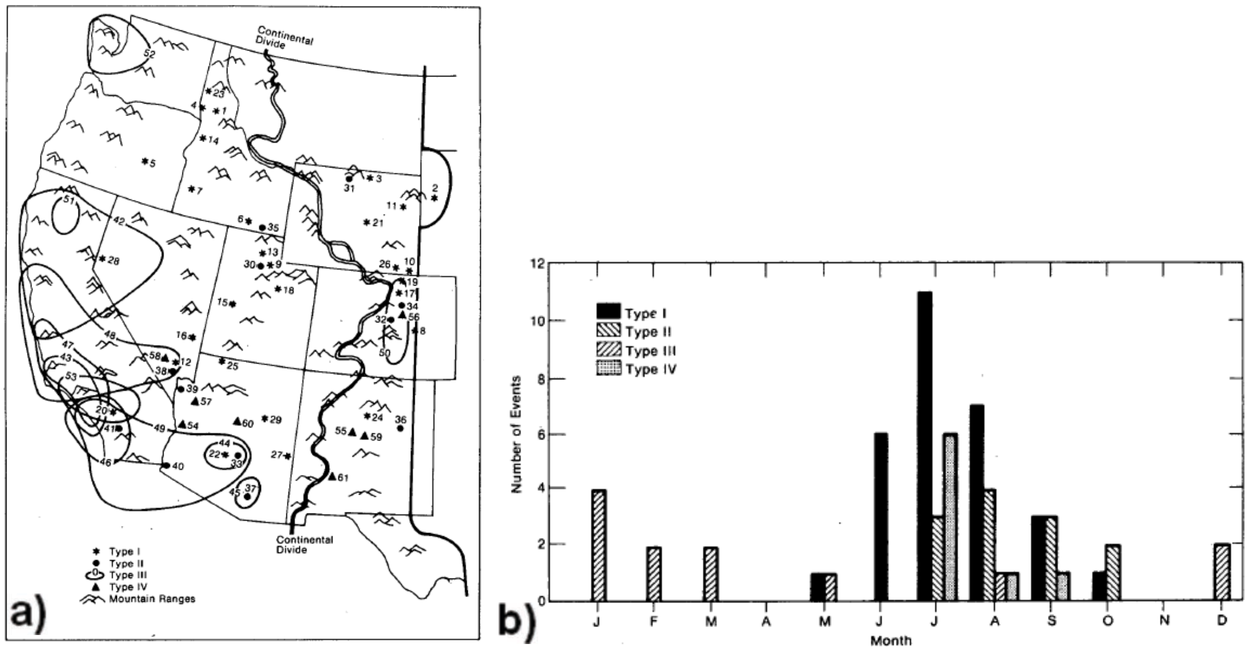


Fig. 1.5: (a) Geographical locations, by event type, of the 61 flash floods studied. Numbers identify the events listed in Table 1 of Maddox et al. (1980). (b) Monthly distribution, by event type, of the 61 flash floods studied. From Maddox et al. (1980).

1.3 Characteristics of High Plains severe weather

The months of June and July in 1979 brought 156 severe weather reports in the High Plains, of which Doswell (1980) studied the common synoptic scale features associated with them and constructed a severe thunderstorm parameter composite chart to illustrate his findings (Fig. 1.6). The purpose of the features shown was to represent the 1200 UTC environment (surface and upper levels) during the first of a series of severe thunderstorm days. Dewpoint temperatures of 45° F or greater along with easterly low level flow were the general surface features found to the lee of the Front Range, promoting moist upslope. Fairly strong, southwesterly 500 hPa flow combined with the low level easterlies and the stronger flow above 500 hPa produced a well sheared vertical wind profile. The area shaded is at the intersection of upslope flow, westerlies aloft, and instability arising from moisture advection; such an environment is conducive for severe thunderstorm development. Overall, the study concluded that High Plains severe thunderstorms are mainly driven by low level features, as significant upper level features were weak. These observations are somewhat similar to those found in Maddox et al. (1979) and (1980), although the upper level flow is southwesterly in Doswell (1980) and northwesterly in the Type I events of Maddox (1980).

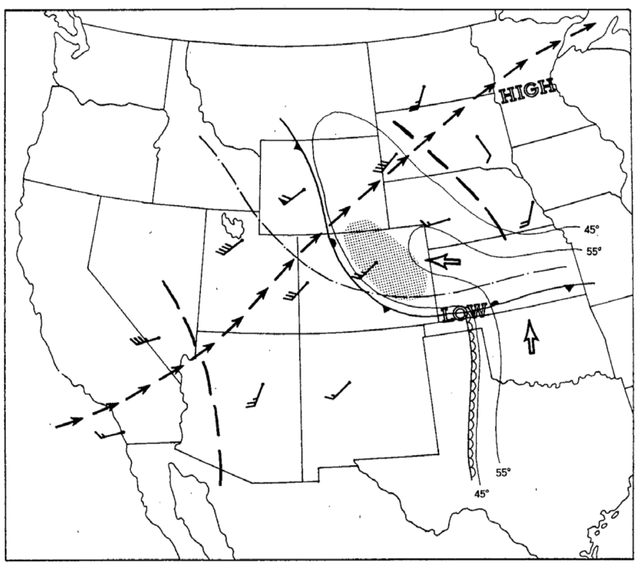


Fig. 1.6: Composite High Plains severe thunderstorm parameter chart. Frontal symbols are conventional, surface isodrosotherms (°F) denoted by fine lines, scalloped line indicated surface dryline, large arrows depict surface low, and “High” and “Low” refer to surface pressure centers. Dash-dot line locates the 700 hPa thermal ridge. Wind barb show 500 hPa winds (full barb signifies 5 m s^{-1}, flag signifies 25 m s^{-1}), and heavy dashed lines locate short-wave trough axes. Chain of arrows is aligned along core of strong high-level winds, above 500 mb. Stippling denotes region of expected severe thunderstorms. From Doswell (1980).

1.4 Flash floods as a severe weather hazard

The understanding of the characteristics associated with severe weather events in the High Plains is important for assessing the subsequent hazardous impacts, such as the threat for damaging hail, wind, tornadoes, and even flooding. Although heavy rainfall may not be perceived as a "severe" weather aspect to the general public, the flash flooding hazard is nevertheless a form of dangerous weather often associated with severe convection. As stated by Doswell et al. (1996), "Rainfall, per se, is a quite ordinary event, which is why it can be difficult to rouse public concern when rainfall becomes life threatening." An environment favorable for deep convection with an ample supply of moisture can result in thunderstorms producing a tremendous amount of rain over a short period of time. Several historical examples of such events have happened over the Front Range of Colorado. These include the Cherry Creek Basin flood of 14 July 1912 (McDonough 1912); the South Platte River flood of 16 June 1965 (brief summary available at http://www.coemergency.com/2010/01/historical-colorado-flood-events.html); the Big Thompson Canyon flood of 31 July 1976; and the Fort Collins flood of 28 July 1997 (Petersen et al. 1999). A more recent severe convective event in which flash flooding occurred in several areas along the Front Range took place on the evening of 6 June 2012, which is the primary case study in this research work. A further in depth analysis of this particular event is presented later in chapter 2. However, it is relevant to note here that what sets apart this event from those aforementioned is the impact of hail on flash flood hazards. One of the hardest hit areas included eastern portions of Colorado Springs, Colorado in El Paso County, as a stationary severe thunderstorm dumped greater than four inches of heavy rain and hail in the city (Fig. 1.7). The aftermath included flooded homes, impaired roofs, stranded motorists, and debris-filled streets.

Fig. 1.7: Steven Carpe sinks in the deep hail in the southwest parking lot of The Citadel mall Thursday, June 7, 2012, after a hail and rain storm hit Colorado Springs on Wednesday night. (Source: Christian Murdock, The Gazette).

1.5 Use of numerical weather prediction for precipitation forecasting

One of the most useful tools for forecasting precipitation, especially in the case of high impact rain events similar to 6 June 2012, is through the guidance provided by numerical weather prediction models. Predicting the future state of the atmosphere at a given time and location is a challenging task for any weather forecaster to achieve on their own. Earth's atmosphere is a dynamical system consisting of various constituents that function and interact in a predictable manner. Consequently, fundamental physical principles are used to describe its behavior. Numerical weather models, which are built upon the physical processes encompassed in these principles, provide much guidance to forecasters in predicting the weather at different spatial and temporal scales.

Prior to initiating the forecast, observational data serves as input in numerical weather models to generate initial conditions that relatively represent the initial state of the atmosphere. However, as the forecast period grows, the resulting weather forecasts become increasingly inconsistent (see Lorenz 1963). Several factors are generally responsible for this effect, one of which is the imprecision of weather observations. Observational data is irregular in terms of its scarcity and that it is not evenly spaced or distributed; not all variables in all places and at all times are observed. Furthermore, the inherent errors in the instruments used to gather the data yield unreliable measurements that may not be representative of the true current state of the atmosphere. Other common factors that may add to forecast inconsistency include the physical parameterizations and resolution of the model being considered. The forecasts produced from these initial conditions, and the chosen approximations to certain physical processes, will have errors that may grow to dominate the forecast over time (see Lorenz 1963). That is, the characteristics of the data and model configurations directly introduce uncertainty into the initial atmospheric state and throughout the forecast. Uncertainty is an intrinsic variable in numerical weather prediction such that no model is perfect. One forecasting system used to manage and effectively represent this uncertainty is an ensemble.

An ensemble forecast system is a series of multiple forecasts valid at the same time from either an individual forecast model with varying initial conditions or from different numerical weather prediction models. Ensemble forecasting demonstrates a practical way of estimating the uncertainty in a forecast by generating a representative array of plausible future atmospheric states, taking into consideration the stochastic nature of weather processes. In this perspective, they can provide information about the range of uncertainty in each forecast situation, the most probable forecast outcome, and the probabilities of those outcomes. Furthermore, such a technique allows weather forecasters to take advantage of multiple forecasts in a way that is most convenient, informative, and comprehensive rather than comparing a few different model forecasts.

If you were to ask someone what aspect of a weather forecast they find most important or care about most, chances are the majority will say the precipitation forecasts. The likelihood (i.e. will it rain or snow), timing (i.e. when will it rain or snow), target location (i.e. where will it rain or snow), and quantity (i.e. how much will it rain or snow) of precipitation are vital elements of any weather forecast from which many societal activities depend on (e.g. agriculture, transportation, and recreational events). Despite the significance of these forecasts to the general community, quantitative precipitation forecasting remains a great challenge in operational meteorology. As the example in Fig. 1.8a shows, there has been considerable improvement in our ability to forecast precipitation amount for the past several decades, regardless of the forecast period. On another note, our level of skill in this area is fairly low during the warm season (defined as June, July, August, and September) compared to other times of the year (Fig. 1.8b). Furthermore, predictive skill is generally lower for higher thresholds of precipitation. Similar observations have been reported in past research studies (Olson et al. 1995, Fritsch et al. 1998, Fritsch and Carbone 2004) which further emphasize our difficulty in generating precise precipitation forecasts, particularly for higher amounts and during the warm season.

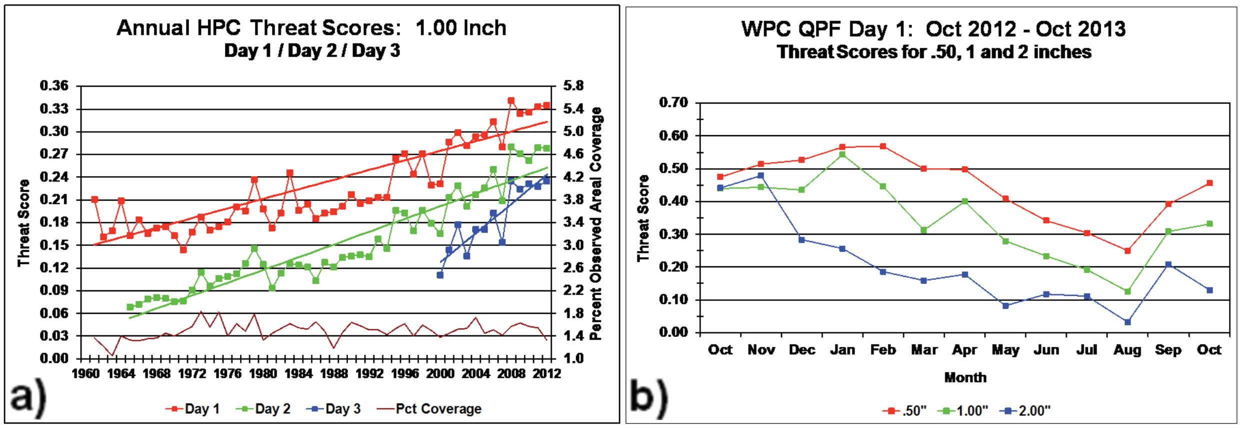


Fig. 1.8: (a) Annual WPC Day-1 / Day-2 / Day-3 Threat Scores and Observed Areal Coverage. (b) Monthly WPC Threat Score and Bias Comparisons (.50", 1.00", 2.00") October 2012 to October 2013. (Source: Weather Prediction Center).

1.6 Predictability of mesoscale convection

The low forecast skill in warm season quantitative precipitation suggests that greater effort should be dedicated towards accurate forecasting on the mesoscale. Unfortunately, the predictability of convective initiation (occurrence, timing and location) is at times ambiguous. Various forcing mechanisms such as fronts, outflow boundaries, and gradients in topography are all important aspects in simulating thunderstorms; a lack thereof could hinder the ability of a mesoscale model in accurately resolving convection (Bernardet et al. 2000) and forecasting precipitation amounts. It also does not help that numerical weather prediction models poorly simulate precipitation events in weakly forced synoptic environments, as typically found during the summer season. For example, model simulation evaluations of warm season precipitation conducted by Davis et al. (2003) and Liu et al. (2006) generally revealed insufficient representations of the timing, distribution, and propagation of rainfall in weakly forced conditions. As discussed in Fowle and Roebber (2003), our limited understanding of precipitation processes adds to the deficiencies or errors in numerical weather guidance. Many studies have considered this limitation in their effort to improve forecasts of warm season convection, and the resulting precipitation, by experimenting with explicit model prediction. Work conducted by Wandishin et al. (2008 and 2010) studied the predictability of mesoscale convective systems (MCSs) using a series of ensemble simulations on a 2-dimensional and 3-dimensional storm-scale model. Both of their simulations were able to adequately reproduce an MCS using preconvective environmental perturbations consistent with 24-hour forecast errors, while reducing the uncertainties of those environmental conditions.

1.7 Explicit convection forecast skill

The poor performance of numerical weather prediction models during the warm season is widely believed to be attributed to the inadequate representation of subgrid convection (Liu et al. 2006), emphasizing our limitations in explicitly forecasting precipitation. This is of no surprise due to the chaotic and small scale nature of convection. Past research studies have used convection-resolving mesoscale models to predict convective initiation, which have shown to produce satisfactory results. For example, Weisman et al. (1997) used a nonhydrostatic cloud model to study the effects of varying grid resolutions on mesoscale convective processes. It was found that grid spacings of 4 km were sufficient to reproduce the structure and evolution of a squall-line-type convective system when compared to coarser resolutions. Other studies that have evaluated high-resolution convective forecasts (2-6 km grid spacing) concluded explicit treatment of convection results in a more accurate depiction of convection characteristics. Fowle and Roebber (2003) measured high forecast skill scores for convective occurrence and mode (or organization) in their high-resolution numerical model forecasts of warm season convection. Similar outcomes followed studies conducted by Done et al. (2004) and Weisman et al. (2008), where their explicit convective forecasts suggested significant value in representing the mode of convection as well as the diurnal convective cycle. Schwartz et al. (2009) found that patterns of convective initiation, organization and behavior were similar between the convection-allowing forecasts retrieved from a 2 km deterministic model and a 10-member, 4 km ensemble. Kain et al. (2008) used daily forecasts from both a convection-allowing 2 km and 4 km model to evaluate sensitivity to spatial resolution, finding that the 2 km version provided a better representation of convective activity. Despite the advantages of explicitly modeling convection, resolving the areal coverage of precipitation is still a problem, especially as the level of convective organization diminishes (Fowle and Roebber 2003).

1.8 Uses of an ensemble prediction system

Warm season quantitative precipitation forecasts are the poorest performance area of forecast systems worldwide (Fritsch and Carbone 2004). One technique that may be used to benefit the prediction of precipitation characteristics is using a short range, high resolution (or convection-allowing) ensemble forecast system. As suggested by Roebber et al. (2004), while high resolution models can help operational forecasters build a conceptual model of mesoscale phenomena, ensemble prediction systems can help quantify forecast uncertainty. The versatility of ensembles has been implemented in several ways regarding its forecasting skill of mesoscale and synoptic weather events. For example, Stensrud and Fritsch (1994b) examined the sensitivity of mesoscale simulations to differences in initial conditions in reproducing a complex MCS event. The effect of initial condition uncertainty on quantitative precipitation forecasts was investigated by Du et al. (1997) during a case of explosive cyclogenesis. Other studies have assessed the forecast skill and uncertainties of global ensemble forecasts in predicting observed notable rain events (Schumacher and Davis 2010, Lynch and Schumacher 2012) or to examine the factors favorable, or detrimental to, the development of observed multi-day heavy rain events (Schumacher 2011, Lynch and Schumacher 2012). Clark et al. (2010) found that forecasts of a mesoscale convective vortex and associated environmental characteristics had better skill from a 10-member convection-allowing ensemble versus a 30-member convection-parameterized ensemble. Clark et al. (2009) compared precipitation forecast skill between a 5-member 4 km and a 15-member 20 km ensemble, finding more accurate precipitation forecasts associated with the convection-allowing ensemble. Overall, the former research studies all share the common use of ensemble methods for gaining qualitative information related to the probability that a weather event will occur and the degree of uncertainty in the forecast. How well certain mesoscale or synoptic scale features are resolved by the multiple forecasts, as well as their frequency and strength, can be very useful to forecasters not only in their predictions of quantitative precipitation but also in communicating their forecasts to the community.

1.9 Communication of weather information

Evaluating the performance of ensembles in simulating mesoscale convection in the mountainous terrain of Colorado is an area of research that has not been visited often. Variation in topography not only adds to the beauty of its landscape, but also plays a role in the development of warm season severe convection (e.g. Toth and Johnson 1985). As put by Morss et al. (2005), Colorado's Front Range is "… a region where variable precipitation, steep terrain, and limited data make estimates of flood risk especially uncertain." It is also a place that holds a history of severe flash flood events (as previously mentioned) and a population that continues to grow, which stresses the importance of flood risk management. Therefore, improving the communication and understanding of hazardous weather information, particularly as it relates to flash flood potentials, is warranted. However, research studies should consider studying how people receive, interpret, and use hazardous weather information as a first step in working towards that objective. Whatever the population of focus is - whether it is the general public, school administrators, or decision makers - how people perceive hazardous weather risks given the associated uncertainties in the forecast will ultimately influence how they choose to respond to the weather situation at hand. These aspects illustrate the important relationship between atmospheric and social science research. This relationship involves translating scientific information for the development of user applications, gathering related feedback from the participants in decision-making, and incorporating their feedback and needs back into the research and development process. Described as the integrated "end-to-end-to-end" research view in Morss et al. (2005) (Fig. 1.9), this form of communication involves constant interactions between interdisciplinary scientific researchers, application developers, and a diverse group of decision makers to produce useful information products (e.g. in this case, flood-risk products), even as science and civilization evolve.

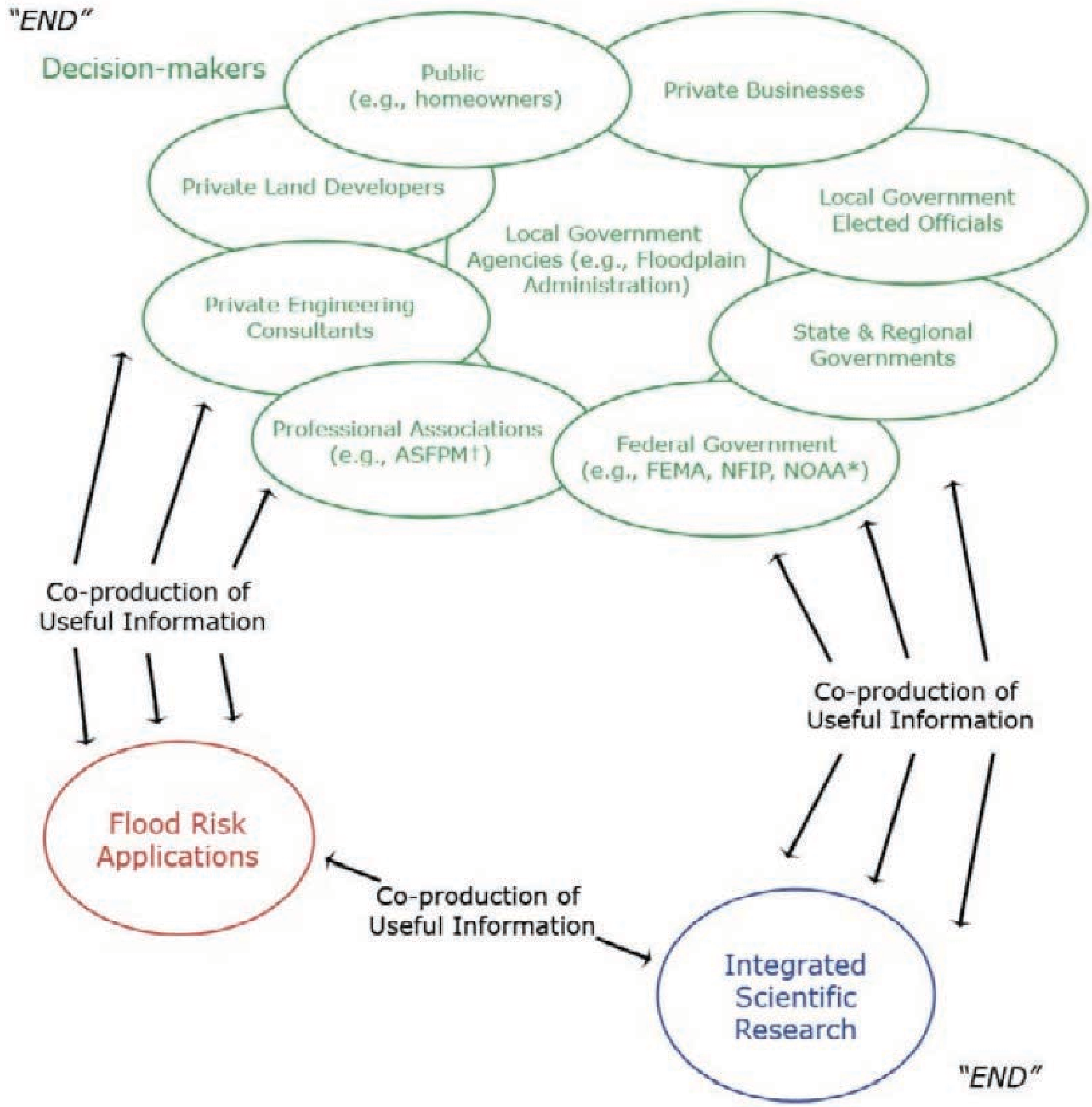


Fig. 1.9: Revised view of research to produce information that is useful in one or more specific societal applications: "end-to-end-to-end" research, illustrated for the case of flood-risk (specifically floodplain) management with diverse, interconnected decision makers. The end-to-end-to-end approach explicitly recognizes the importance of multidirectional communication; sustained interactions among researchers, application developers, and multiple decision makers; and multiple iterations around the loop to coproduce knowledge and tools. Integrated scientific research includes disciplinary and interdisciplinary work in statistics, climatology, meteorology, hydrology, engineering, geography, and the social sciences and humanities. The two ENDs in the figure represent the two ENDs in end-to-end research (Fig. 1 of Morss et al. 2005); end-to-end-to-end research signifies iteration between these two ends.

Several unique past research studies have investigated the “end-to-end-to-end” research cycle in terms of the communication and interpretation of weather information products by decision makers, particularly emergency managers. For example, Baumgart et al. (2008) used severe weather questionnaires and simulated weather scenarios to develop a decision-making model describing the use and assessment of weather information, as well as the decisions made by emergency managers during severe weather. The communication process of emergency managers during severe weather was characterized by League et al. (2010) in terms of how they acquired, interpreted, verified, and applied the information to make warning decisions. Working with a slightly broader group of decision makers, Schumacher et al. (2010) examined the flow and interpretation of severe weather information after a warning is issued by the National Weather Service. The general conceptual framework of the decision-making process illustrated by these studies has revealed how uncertainties in the understanding of weather information and perceptual cues carry through and influence the decisions made thereafter.

The promising opportunities of ensemble prediction systems in forecasting warm season mesoscale convection, as well as the lack of documentation on how weather forecast uncertainty is communicated to decision makers, has greatly inspired this thesis work into integrating both of these aspects. In particular, the convective activity that took place along and east of the Front Range in Colorado on 6 June 2012 serves as the primary case study in this research, as it caused an estimated $321.1M in damage and was among the most costly Colorado storms since 1984 (Rocky Mountain Insurance Information Association 2012). Short-range ensemble forecasts of both explicit and parameterized-convection are used as an evaluation tool to determine 1) how well the ensemble was able to resolve the mesoscale features responsible for the convection, 2) the degree of uncertainty within these forecasts in relation to precipitation estimates, and 3) how illustrating that uncertainty within various forecast representations is understood by Front Range decision makers, especially regarding the risk of flash flooding. The long term goal of this research is to develop and add reliable probabilistic forecast products to the “toolbox” of decision makers to help them better assess hazardous weather information and improve warning notifications and response.

CHAPTER 2

6 – 7 JUNE 2012 FRONT RANGE CASE STUDY

2.1 Overview of the 6 June 2012 evening severe convection

This section will discuss the contributions made by various meteorological processes, on both the synoptic and mesoscale, that collectively generated the severe convection along the Colorado Front Range on 6 June 2012. This warm season convective event was characterized by hazards commonly associated with severe weather, that is to say tornadoes, hail, wind, and heavy rainfall. Consequently, the basis of this discussion accentuates the primary ingredients necessary for severe thunderstorm development (moisture, instability, a lifting mechanism, and wind shear; see Doswell 1987) and heavy precipitation (moisture and duration of convection, see Doswell et al. 1996). Following is an analysis of the observed accumulated precipitation throughout the convective event as it relates to observed radar reflectivity.

2.1.1 Synoptic scale analysis

On 0000 UTC 6 June 2012, a negatively tilted 300 hPa trough was located over the Pacific Northwest (not shown). Meanwhile, a broad ridge and trough were situated in the Central Plains and eastern United States, respectively. A surface low-pressure system was located in south central Montana, with a trailing cold front extending from western Wyoming southwestward into southern Utah (Fig. 2.1). No significant weather was occurring at this time in Colorado, with general cloud cover over the High Plains and surface temperatures (°F) in the low to mid 80s east of the foothills. Gusty southeasterly winds were also present over much of eastern Colorado, likely as a result from the pressure gradient enforced by a 989-hPa low in southern Montana. As discussed later, how the frontal boundary associated with this surface low is resolved by our ensemble prediction systems plays a role in their probabilistic weather forecasts generated for 6 June 2012.

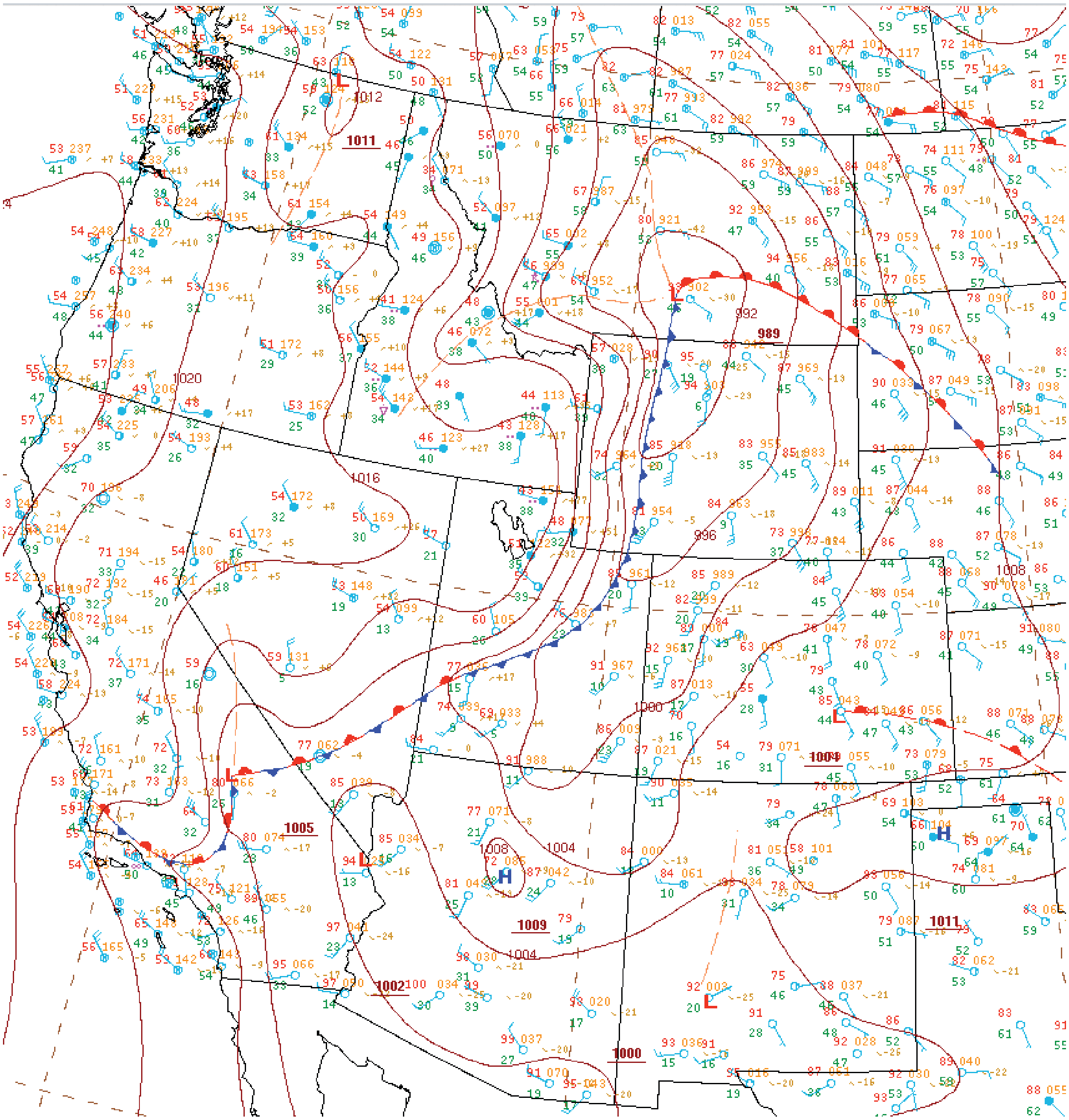


Fig. 2.1: Weather Prediction Center's surface analysis for the western United States valid on 0000 UTC 6 June 2012.

By early morning on 1200 UTC 6 June, there were three notable synoptic scale features at 300 mb: 1) an upper level trough in the western United States, 2) a weak ridge in the Central Plains, and 3) a very extensive trough in the Northeast (Fig. 2.2a). As this case study pertains to those events in Colorado, the discussion herein will be addressing features mainly in the western half of the United States. The large scale flow interaction between the Pacific trough and the Central Plains ridge allowed for a broad area of diffluent flow east of the Northern Rockies. A jet streak exceeding 70 knots had encircled the base of the western trough and lifted its base as it moved downstream. As a result, Colorado was currently under weak southwesterly flow aloft at the southern fringe of this trough. The overall morning upper level pattern continued into 0000 UTC June 7, although stronger southwesterly flow aloft was present and extended from northern Arizona into central Colorado (Fig. 2.3a). Furthermore, the jet streak was downstream of the trough; Colorado became under the right-entrance region of the jet where broad upper level divergence and induced upward vertical motion are implied, via straight-jet dynamics (Uccelinni and Johnson 1979).

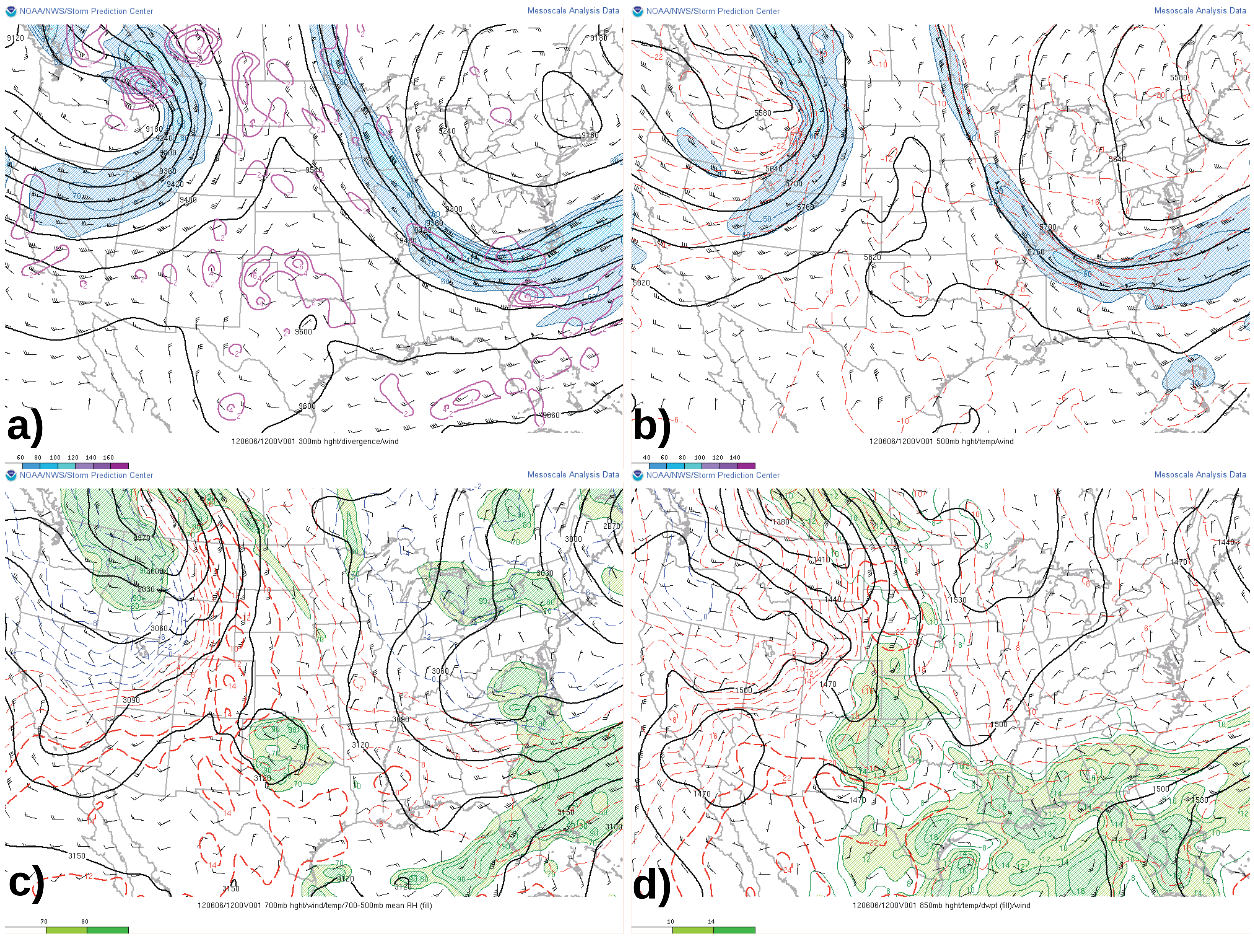


Fig. 2.2: (a) 300 hPa height (meters), divergence (pink contours), wind (barbs in knots), isotachs (blue color shading in knots) at 1200 UTC 6 June 2012. (b) 500 hPa height (meters), temperature (dashed red contours), wind (barbs in knots), isotachs (blue color shading in knots) at 1200 UTC 6 June 2012. (c) 700 hPa height (meters), wind (barbs in knots), temperature (dashed red-above freezing, dashed blue-below freezing contours in Celsius), and 700-500 hPa mean relative humidity (green shading) at 1200 UTC 6 June 2012. (d) 850 hPa height (meters), temperature (dashed red-below freezing, dashed blue-above freezing contours in Celsius), dewpoint temperature ≥ 8° Celsius (green color shading), and wind (barbs in knots) at 1200 UTC 6 June 2012.

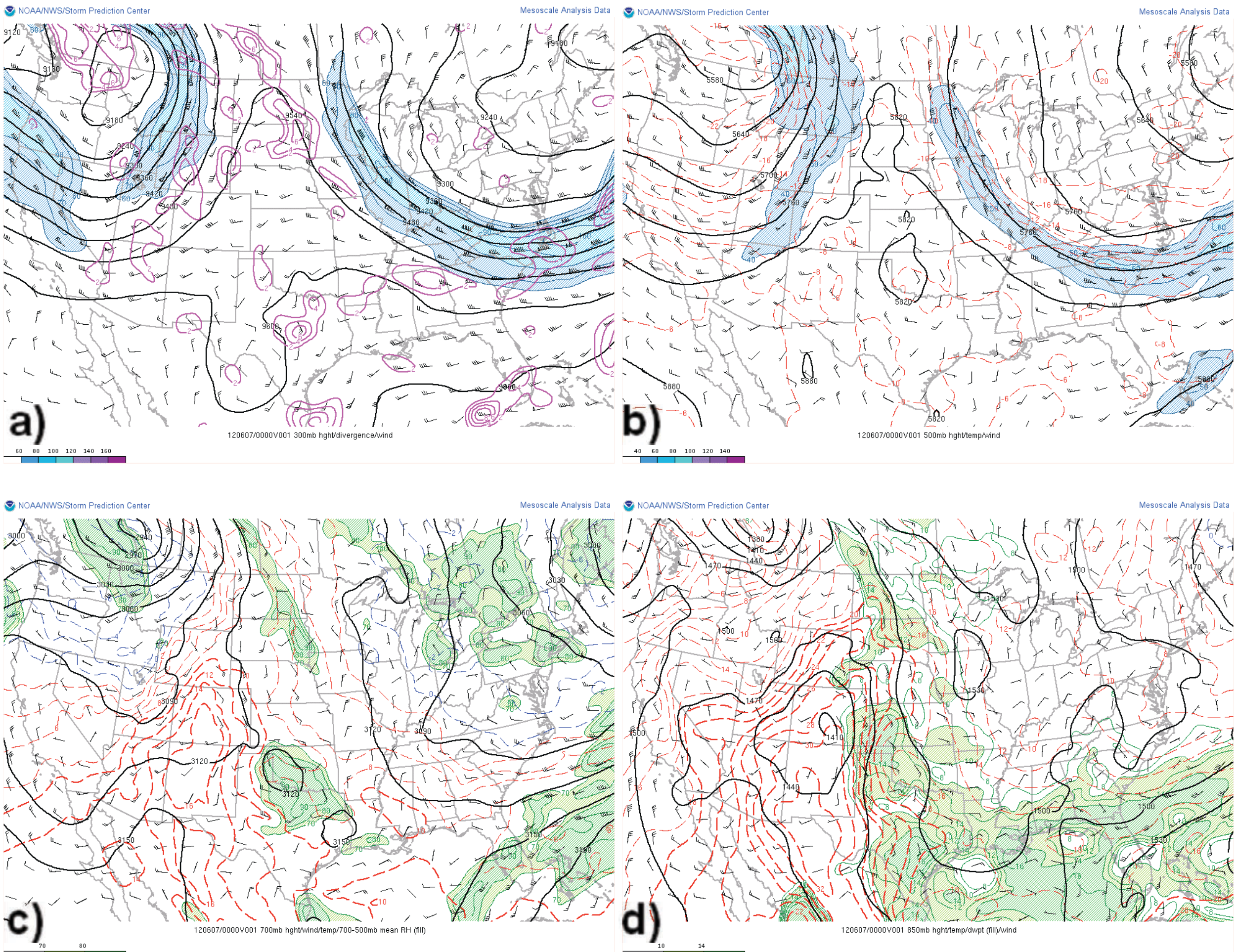


Fig. 2.3: As in Fig. 2.2., except at 0000 UTC 7 June 2012.

A similar trough-ridge-trough synoptic pattern was also present at 500 hPa on the morning of 6 June (Fig. 2.2b) and continued through 0000 UTC 7 June (Fig. 2.3b). Compared to the morning analysis, stronger westerly and southwesterly winds dominated the flow across Colorado. There was also some weak positive vorticity advection in the High Plains in association with a very subtle shortwave feature upstream of the ridge (not shown), possibly suggesting their insignificance to diagnosing the convective activity that evening. Despite this subtlety, the 500 hPa synoptic pattern is similar to those categorized as Type I events studied by Maddox et al. (1980).

While cold air advection at 700 hPa was found on 1200 UTC June 6 (Fig. 2.2c), this turned around by the evening as warm air advection had set into place over the High Plains of Colorado, along with southeasterly flow (Fig. 2.3c). As for the resulting change in the surface pressure field, initially there was an area of lower pressure evident by the dip in the 1470 m isoheight on 1200 UTC 6 June in the lower levels (Fig. 2.2d). This area of low pressure deepened throughout the afternoon and into the evening over southwest Colorado by 0000 UTC June 7, looking more synoptic scale in nature and achieved an isoheight of 1410 m (Fig. 2.3d). The south and southeasterly flow downstream of this system helped to advect warm, moist air from the Southern Plains into eastern Colorado throughout the day on 6 June. In summary, the primary meteorological factors gathered from the synoptic scale observations include broad upper level divergence, decent vertical wind shear, and a buoyant air mass (further supported by Denver, Colorado soundings discussed in section 2.1.2b). As will soon be discussed, these elements played a part in producing the severe convection during the late afternoon into the evening hours on this day.

2.1.2 Mesoscale analysis

2.1.2a Surface

As previously mentioned, a surface low pressure system was situated over south central Montana on 0000 UTC 6 June, with a trailing cold front extending from western Wyoming southwestward into southern Utah (Fig. 2.1). As the 300 hPa jet moved downstream of the upper level trough and lifted its base by 1200 UTC 6 June, the associated surface low moved northwest and occluded. The occluded low was present over southern Alberta, Canada, and had a trailing cold front arcing from the triple point, southeast across northeastern Montana, and then southwestward into northeast Colorado (not shown). Furthermore, this cold front was weak in terms of the gradient in temperature across the boundary, especially for its southern extent. Surface temperatures (°F) were generally in the upper 50s (low 60s) behind (ahead) of the cold front (Fig. 2.4a). Meanwhile, surface winds were light and generally from the southeast over the High Plains. It is interesting to note that at this time, there seemed to have been the development of a Denver Cyclone, a terrain-induced cyclonic circulation that typically develops near Denver (Wilczak and Glendening 1988, Wilczak and Christian 1990). Although not always the case, the development of a Denver Convergence Vorticity Zone (DCVZ) can also be associated with a Denver Cyclone, as will be discussed shortly.

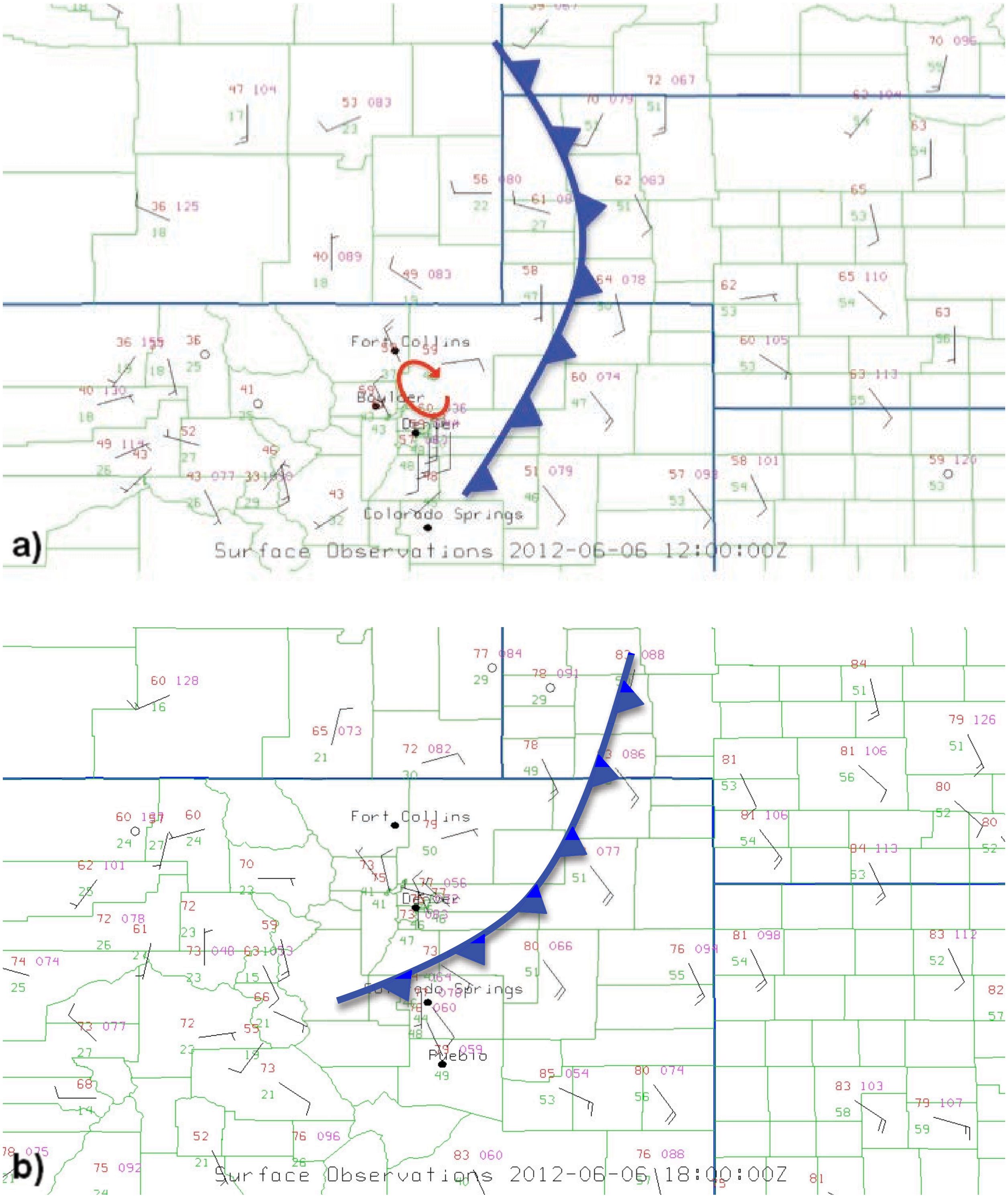


Fig. 2.4: Surface METAR observations and cold front analysis for (a) 1200 UTC 6 June 2012 and (b) 1800 UTC 6 June 2012. Red circular arrow in (a) subjectively identifies the counter-clockwise circulation associated with that of a Denver Cyclone.

By 1800 UTC 6 June, the weak cold front had progressed further east, and extended from western South Dakota arcing southwestward into south central Colorado (Fig. 2.4b). Surface temperatures (°F) had climbed to the low 80s across much of the High Plains, with upper 70s closer to the foothills. Surface winds were gusting to as high as 30 knots from the southeast (not shown), advecting warm, moist air from the Southern Plains into eastern Colorado. This advection of warmer temperatures and higher dewpoint air from the Southern Plains into the boundary layer over the High Plains aided in the development of an unstable air mass, and continued throughout the afternoon. These characteristics of atmospheric instability and the vertical shear profile (as described in the synoptic analysis) not only demonstrate an environment conducive for severe thunderstorm development, but also are findings comparable to those concluded in Doswell (1980) for High Plains severe convection.

According to the Weather Prediction Center's surface analysis on 2100 UTC 6 June, it seems as though the southern extent of the cold front in northern Colorado had been analyzed as a stationary front (Fig. 2.5). This stationary front had extended from the triple point in southwestern North Dakota, southwestward through western Colorado. It is uncertain as to why such a boundary was evaluated at this time. It is hypothesized that the temperature gradient might have been washed out given how weak it was. Nevertheless, attention will be given to the atmospheric conditions present just a couple of hours before, where visible satellite imagery showed a cumulus field developing over the higher terrain of north central Colorado at 1900 UTC June 6 (Fig. 2.6a). This is as a result of the influx of the southeasterly warm, moist air interacting with a convergence boundary that extended from extreme southwest Morgan County, southwestward to extreme southeastern Douglas, County, as seen in the KFTG (Denver, Colorado) radar reflectivity and surface winds (Fig. 2.6b). This convergence boundary is likely the DCVZ, a common feature attributed to the contrasting terrain in northern Colorado and has been observed by several observational studies to be associated with the formation of severe weather. According to the American Meteorological Society Glossary of Meteorology, the DCVZ is “a mesoscale flow feature of convergent winds…usually orientated north-south, just east of the Denver, Colorado area. The cause of the feature is an interaction of southerly low-level flow with an east-west ridge known as the Palmer Divide extending onto the eastern Colorado plains to the south of Denver.” Szoke et al. (1984) observed the initiation of convection and the intensification of a tornadic storm at the southern end of a convergence-vorticity zone over and north of Denver. A case study of a Denver hailstorm by Blanchard and Howard (1986) studied flooding and severe hail in the vicinity of the terrain-induced feature. Similar findings have also been observed in the case study presented in this chapter.

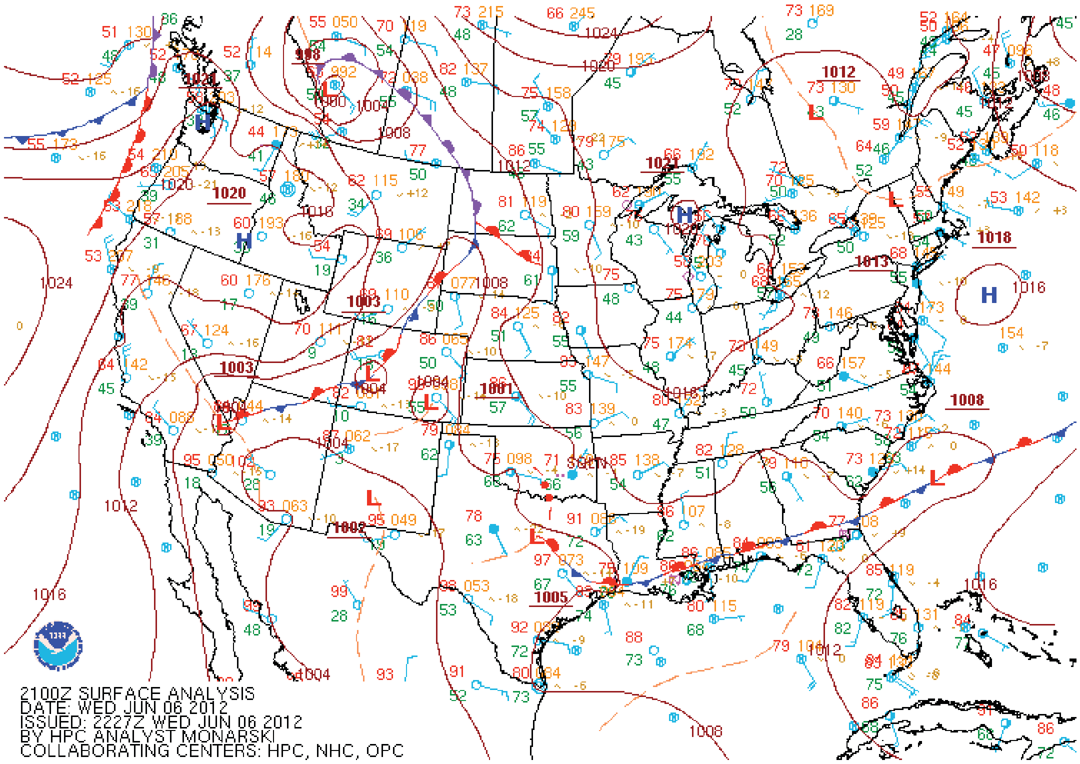


Fig. 2.5: Weather Prediction Center’s surface analysis for the United States (CONUS) valid on 2100 UTC 6 June 2012.

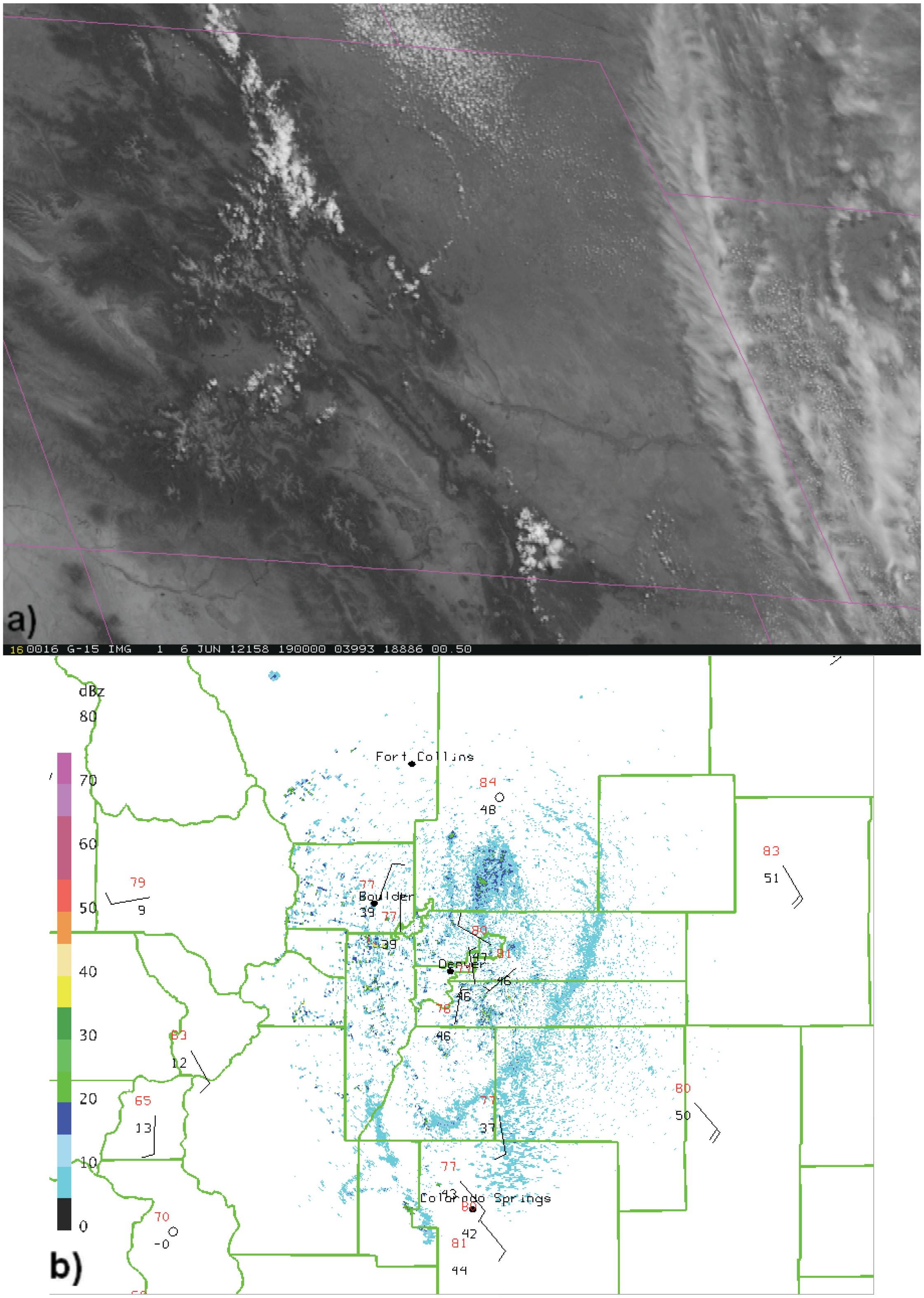


Fig. 2.6: (a) Visible satellite imagery of eastern Colorado at 1900 UTC 6 June 2012. (b) KFTG Denver radar reflectivity and METAR surface observations at 1900 UTC 6 June 2012.

It is of interest to compare the initial stages of the Denver Cyclone and associated DCVZ identified in Wilczak and Glendening (1988) with the one recognized in this case study. Wilczak and Glendening used an array of observations to characterize a Denver Cyclone that occurred on 1 August 1985. As shown in Fig. 2.7a, signs of a developing circulation were observed at 0900 UTC as suggested by a general cyclonic turning of the winds. A northeast-southwest orientated boundary was also present in the northern portion of their observation network. Compared to the 6 June 2012 event, the early stages of a developing circulation were not observed (at least subjectively) until 1100 UTC (Fig. 2.7b). Although not indicated well by radar, the surface winds also suggested a northeast-southwest boundary within similar vicinity. It was not long before the cyclonic circulations in both studies became fairly well-defined, with southerly flow over the plains and northerly flow along the foothills, and with a north-south convergence boundary to the east of Denver (not shown). These comparisons illustrate the value and general consistency of a surface observation network detecting a mesoscale terrain-induced circulation, as well as demonstrating the consensus between research studies.

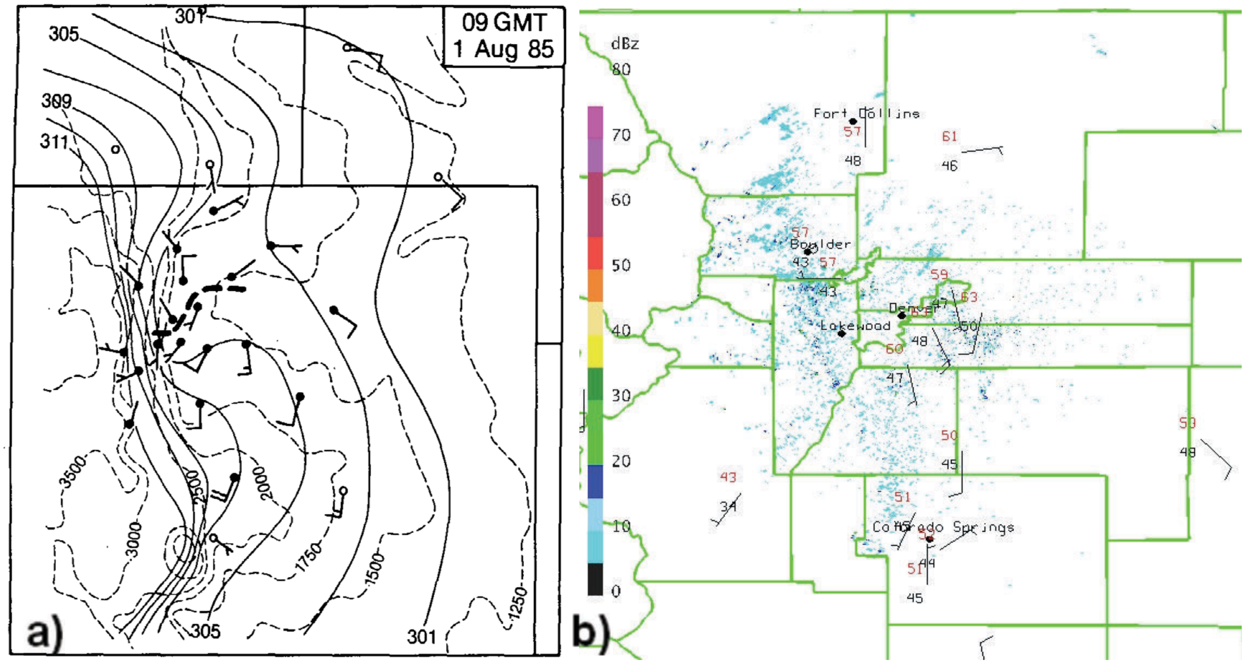


Fig. 2.7: (a) Surface observations of wind velocity and potential temperature at 0900 UTC 1 August 1985. Potential temperature (solid lines) contour interval is 2 K; selected terrain contours are shown with thin dashed lines. The convergence zone is shown with a heavy dashed line. From Fig. 4a of Wilczak and Glendening (1988). (b) Surface METAR observations and KFTG radar reflectivity at 1100 UTC 6 June 2012.

The cumulus field continued to build along this convergence boundary such that by 2100 UTC 6 June, convection began to initiate on the northern edge of the boundary (Figs. 2.8a, b). This initiation of convection extended into southeast Wyoming, likely due to the moist upslope flow along the Cheyenne Ridge (not shown). The advection of warm, moist air from the Southern Plains continued into the evening across the High Plains as convection continued to develop south and west along the westward moving convergence boundary. This direction of motion is theorized to be enhanced by the convective outflow from the existing cells.

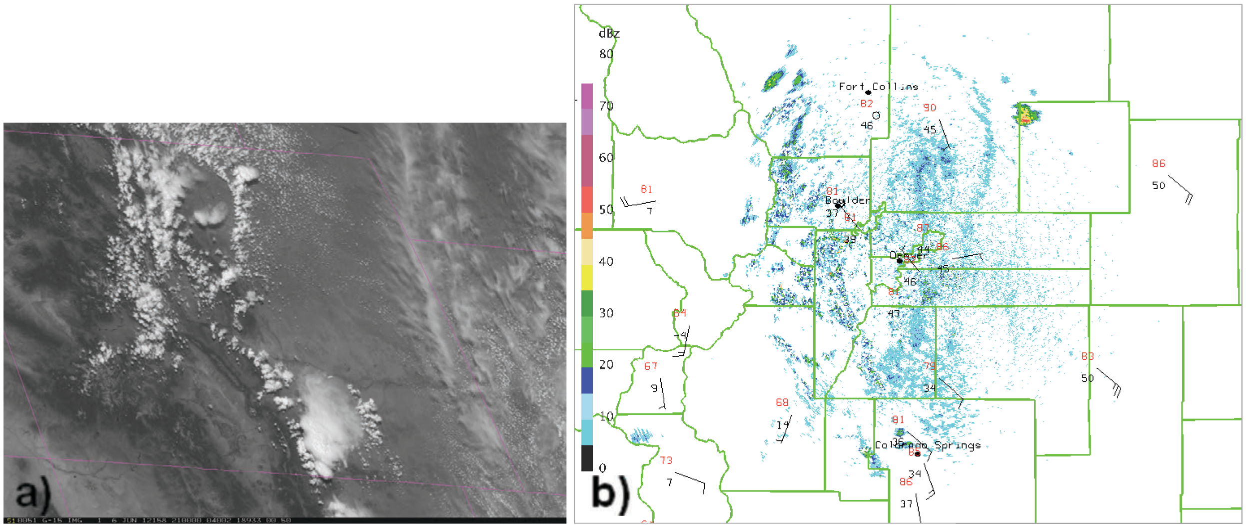


Fig. 2.8: (a) Visible satellite imagery of eastern Colorado at 2100 UTC 6 June 2012. (b) KFTG Denver radar reflectivity and METAR surface observations at 2100 UTC 6 June 2012.

In general, the convergence boundary that developed during the early afternoon on 6 June served as the lifting mechanism to condense the southeasterly warm, moist air spreading across the High Plains of Colorado. This advection of warm, moist air increased the latent instability in the atmosphere through the release of latent heat (subsequent to condensation) into the developing clouds, thereby increasing their temperature and buoyancy compared to the surrounding environment. This reaction allowed for further cloud development and ultimately led to the convection building parallel to the convergence boundary east of the foothills.

2.1.2b In-depth analysis of severe weather indices

Prior to describing the profile of the environment on 6 June 2012 in terms of severe weather thermodynamics, wind shear, and other related characteristics, it is worth distinguishing between the two sources of information considered in this analysis. The soundings retrieved for Denver are *observational data*, whereas the Storm Prediction Center mesoanalysis fields should be considered as an *estimate* of various severe weather parameters. Therefore, it is important to keep in mind that while the mesoanalysis may illustrate a reasonable representation of the environment, it is an approximation of reality and not essentially the truth. Furthermore, observational data have errors that may lead to a misrepresentation of the environment, as mentioned in section 1.5.

One of the main ingredients necessary for severe thunderstorm development is instability, which can be assessed by studying various thermodynamic parameters. An example is Convective Available Potential Energy (CAPE), which is a measure of the amount of energy available for convection. In this assessment, the Mixed Layer CAPE (MLCAPE) is investigated as it is a better representation of the environmental conditions given there is always mixing occurring in the boundary layer. This value represents the mean potential energy available to an air parcel originating in the lowest 100 hPa when it is lifted to its level of free convection (LFC). The LFC is the level at which the temperature of a lifted parcel becomes warmer than the environmental temperature, and is able to freely accelerate upward to the equilibrium level (EL). At that point, the lifted parcel becomes cooler than the environmental temperature and is no longer positively buoyant. These variables, and others, are identified using a Skew-T log P diagram, a thermodynamic diagram commonly used in weather analysis.

The Denver sounding at 1200 UTC 6 June showed dry conditions throughout the atmosphere, with a low MLCAPE value and a high Mixed Layer Convective Inhibition (MLCINH) value (Fig. 2.9). MLCINH may also be referred to as a capping layer, a region where the temperature of a parcel lifted from the lowest 100 hPa is cooler than the environmental temperature; thus, it is a stable air layer. The stable layer in this sounding is found between 850 hPa and 750 mb. MLCINH also describes the amount of energy needed to warm the boundary layer in order for surface air parcels to reach the LFC; this capping layer aloft must be overcome for the initiation of convection. At this time, nocturnal radiational cooling explains the stable air layer near the surface. The dry conditions present at the surface and aloft indicate a large dewpoint depression; thunderstorm development was unlikely as any uplift will face difficulty in saturating the air.

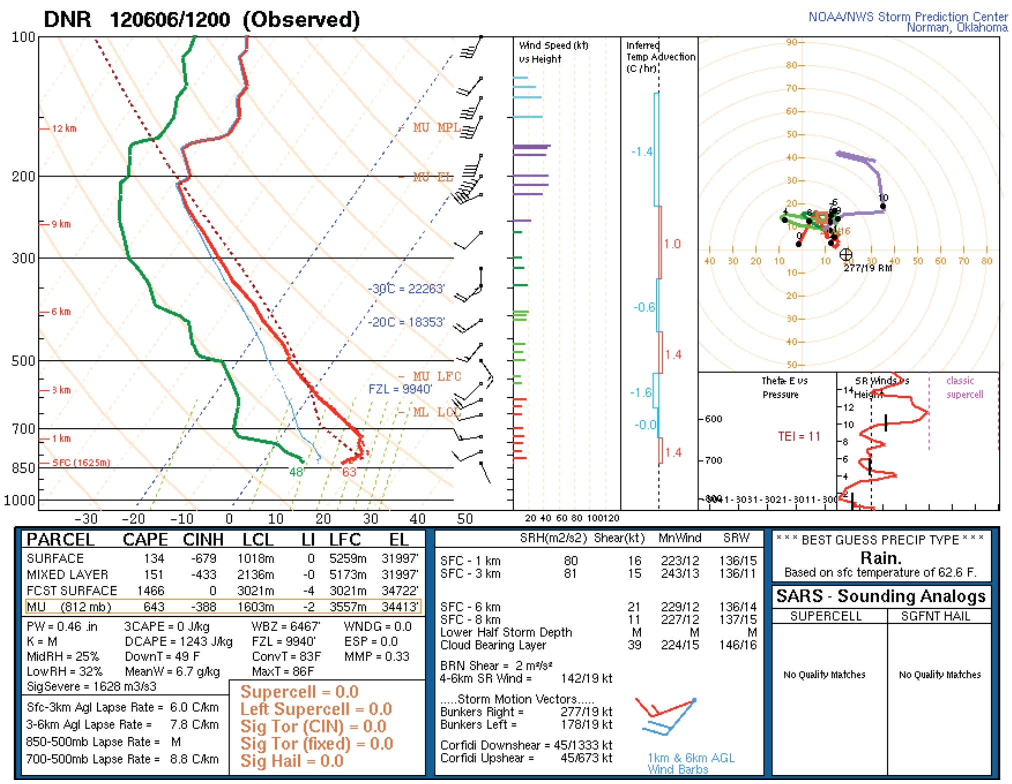


Fig. 2.9: Denver, Colorado upper-air sounding at 1200 UTC 6 June 2012.

A special sounding taken by the Denver/Boulder Weather Forecast Office (WFO) at 1900 UTC 6 June showed northerly winds in the lowest levels of the troposphere at Denver (Fig. 2.10a). This is a reflection of the light northerlies along the foothills behind the DCVZ. The value of MLCINH had greatly reduced, as suggested by the weakened cap likely due to the daytime heating and low level warm air advection (especially the advection of higher dewpoint air) east of the foothills and into the High Plains. Elsewhere at this time period, MLCAPE values of 1000 Jkg^{-1} or more began to spread into the High Plains (Fig. 2.11a). By the early afternoon, and before convection initiated, MLCAPE values had exceeded 2000 Jkg^{-1}over much of the High Plains (Fig. 2.11b). These large values of MLCAPE are as a result of three factors: 1) low level warm air advection, aiding to the development of a sufficiently buoyant air mass 2) steep lapse rates, as shown by the 1900 UTC Denver sounding and 3) strong diabatic heating under mostly clear skies, as was shown by the visible satellite imagery at the same time stamp. These factors combined helped to destabilize the atmosphere during the afternoon and allowed thunderstorms to build vertically quickly.

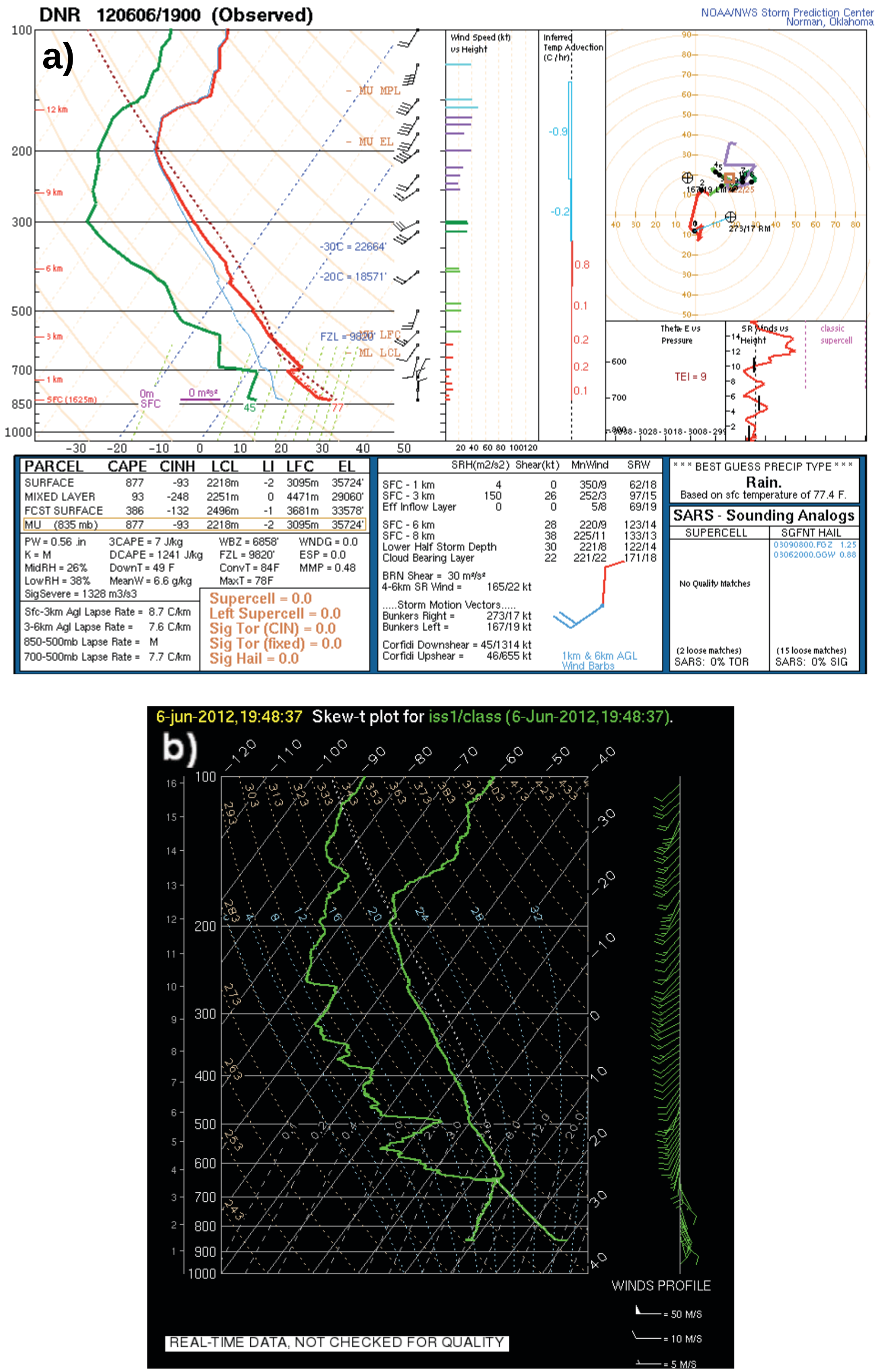


Fig. 2.10: (a) Denver, Colorado sounding at 1900 UTC 6 June 2012. (b) Fort Morgan Municipal Airport sounding at 1948 UTC 6 June 2012.

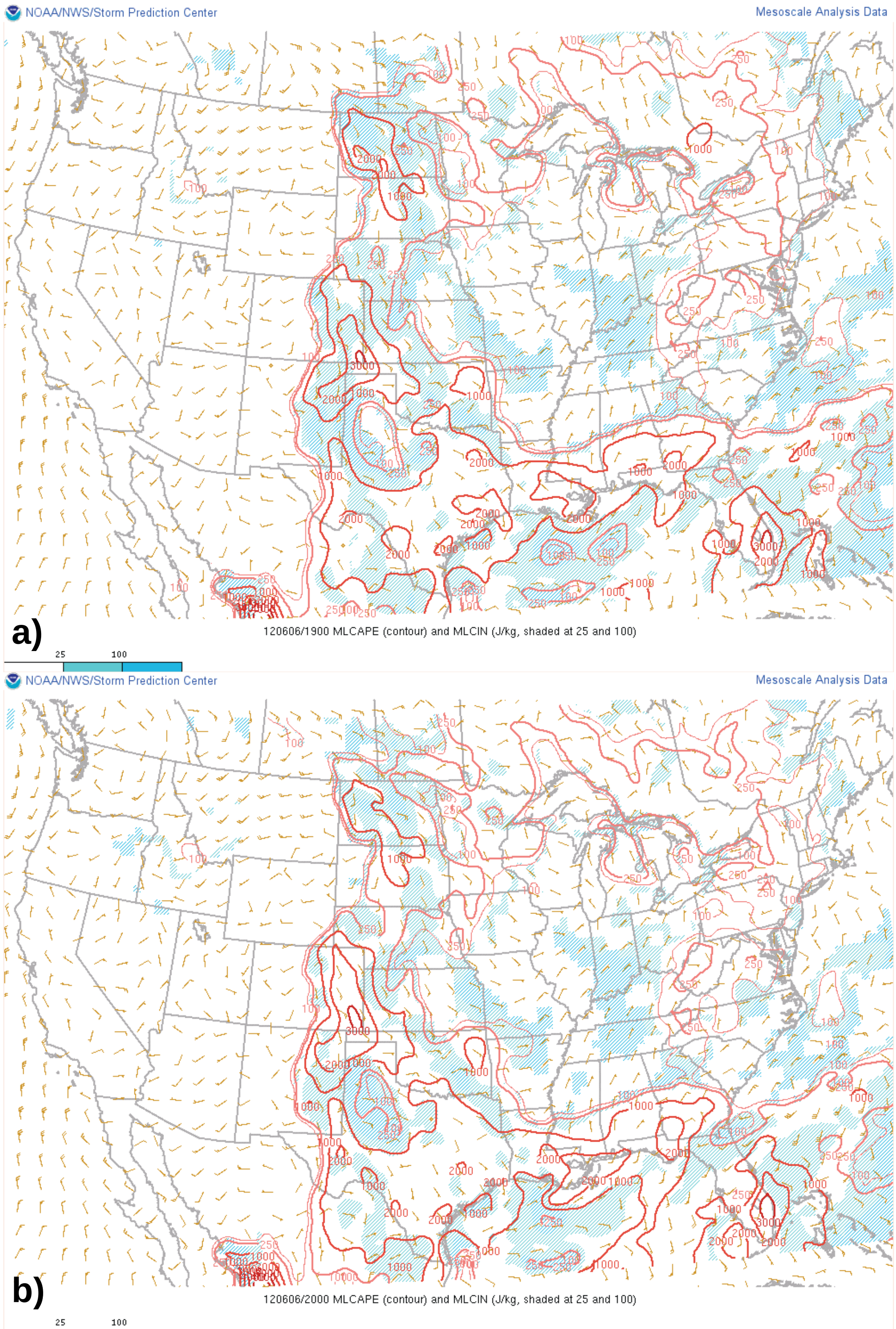


Fig. 2.11: Storm Prediction Center mesoanalysis fields of MLCAPE (red contours, Jkg^{-1}) and MLCIN (blue shading for 25 Jkg^{-1} and 100 Jkg^{-1}) at (a) 1900 UTC 6 June 2012 and (b) 2000 UTC 6 June 2012.

The 1900 UTC Denver sounding was compared to the 1948 UTC Fort Morgan sounding (Fig. 2.10b) to verify that the conditions on either side of the boundary were relatively the same other than a shift in the wind. The Fort Morgan sounding was retrieved from the Deep Convective Clouds and Chemistry (DC3) Experiment upper air research products archive (for more information about the field campaign, visit https://www.eol.ucar.edu/field_projects/dc3). Dry conditions characterized the boundary layer from both locations. Northerly (southerly) surface winds were observed at Denver (Fort Morgan), indicating its position to the west (east) of the boundary. The dewpoint temperature profiles throughout the boundary layer of both locations were similar, with only a difference of a few degrees between the two. While this observation suggests a very weak dewpoint gradient, it is not sufficient to demonstrate the presence of a dryline feature; the surface dewpoint temperature gradient across boundary was considered negligible in this analysis.

The Denver sounding at 0000 UTC 7 June was characterized as an inverted “V” sounding, showing dry air in the lower troposphere and nearly saturated air in the upper levels (Fig. 2.12). This type of sounding is favorable for severe weather given the likelihood for strong surface winds. These strong winds would be as a result of the negatively buoyant evaporatively cooled air aloft that accelerates down towards the surface. Local storm reports that evening on 6 June reported surface wind gusts reaching almost 70 mph at the Denver International Airport (Fig. 2.13a), and 60 mph near the Peterson Air Force Base northeast of Colorado Springs, Colorado (Fig. 2.13b). It is important to note that this particular sounding is not representative of the environment favorable for heavy rainfall given the dry conditions of the boundary layer. At this time, the convergence boundary had essentially passed over Denver and dissipated (Fig. 2.19a). Relative to Denver, slightly more moist conditions were present further south and east, where convection was developing and 1 to 2 inches of precipitation had fallen by this time period (Figs. 2.18a and 2.20a).

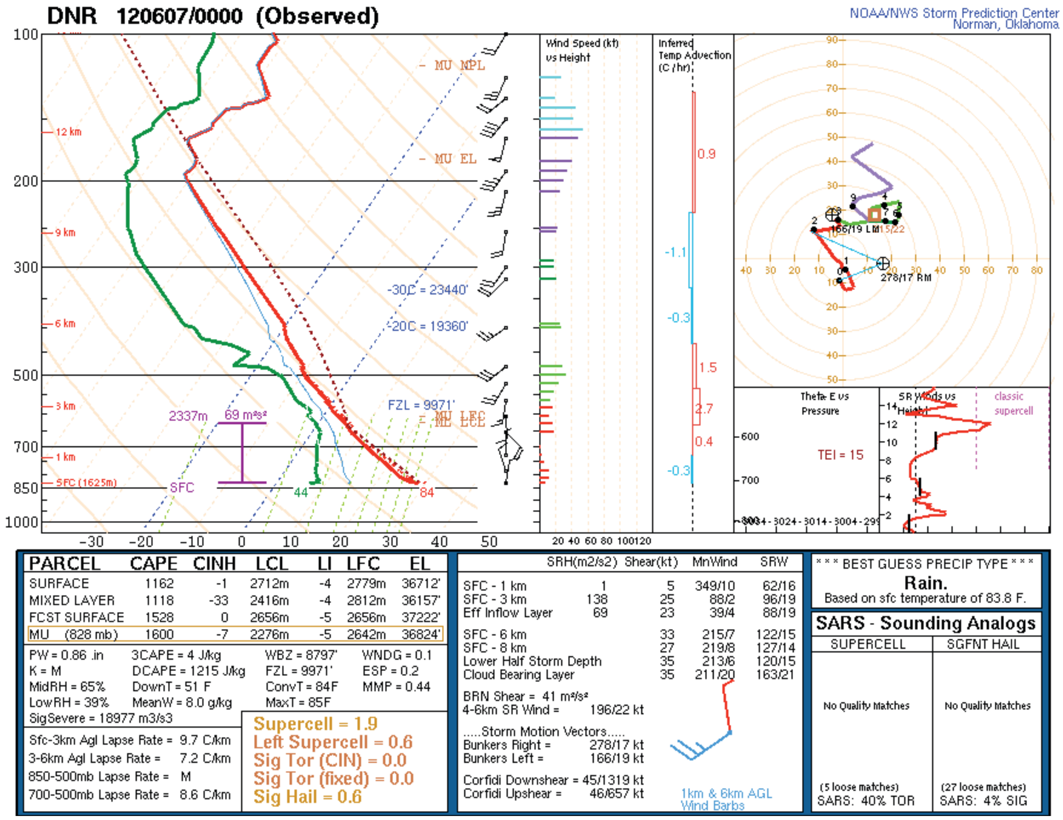


Fig. 2.12: Denver, Colorado sounding at 0000 UTC 7 June 2012.

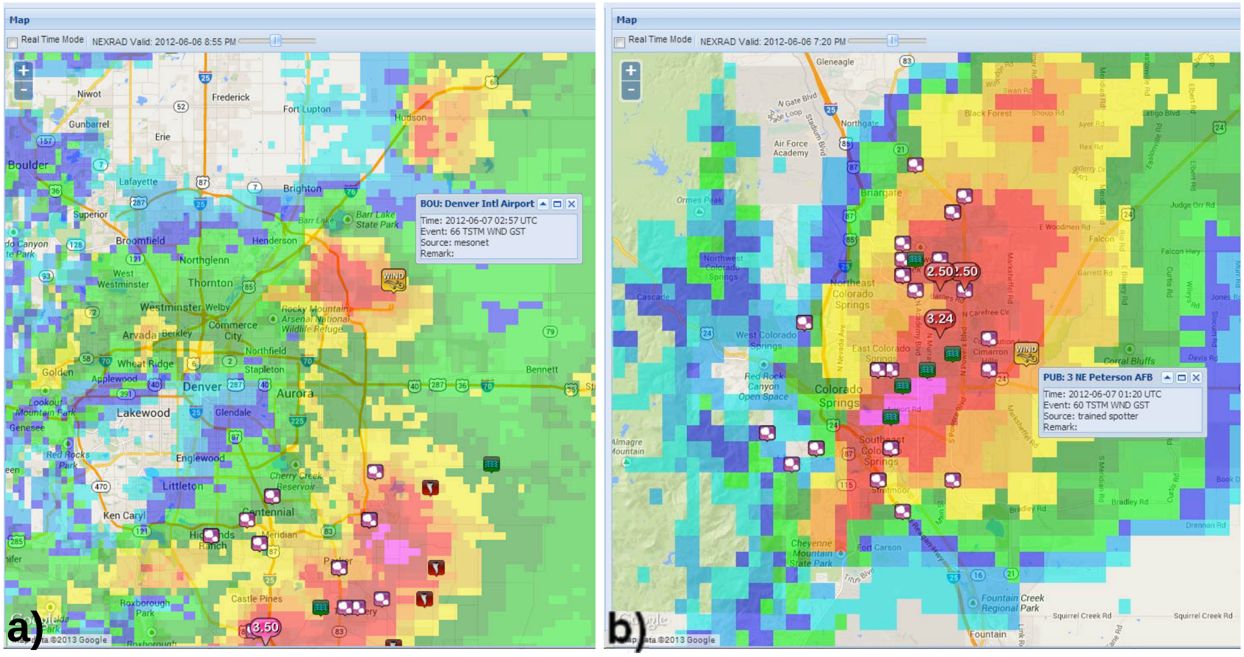


Fig. 2.13: (a) Local storm report of a 66 mph wind gust at Denver International Airport, and associated Denver convective cell. (b) Local storm report of a 60 mph wind gust at Peterson Air Force Base, and associated Colorado Springs convective cell.

Vertical wind shear plays a role on storm type, and promotes storm organization and longevity (e.g. Weisman and Klemp 1984). In particular, the 0-6 km shear is used frequently for the prediction of supercells (Craven and Brooks 2004). The vertical wind profile of the evening Denver sounding showed a 0-6 km shear vector of 33 knots; this is usually regarded as moderate shear (Markowski and Richardson, 2010). The formation of supercells, storms that have persistent and deep rotating updrafts, are commonly associated with deep shear values greater than approximately 35 knots throughout this depth (Markowski and Richardson, 2010). Therefore, the environment was just about favorable for supercells. The common severe weather hazards associated with supercells include damaging winds, large hail, and sometimes weak to violent tornadoes. Local storm reports from the 6 June convective event described wind gusts as high as 70 mph (as previously mentioned), hail from the size of marbles to golf balls, and short-lived tornadoes. However, several past research studies have suggested that supercells can occasionally be characterized as productive heavy precipitation producers as well (e.g. Doswell 1993, 1999; Smith et al. 2001). The 6 June severe convective event is a good example of such a situation, as two supercell storms were responsible for numerous flash flood events across eastern portions of the Denver and Colorado Springs metropolitan areas. What is most interesting about these flood events is that both heavy precipitation and abundant amounts of hail were the culprits.

2.2 Ingredients for heavy rainfall and hail

Most people are concerned about the quantitative character of a forecast, that is, when is it going to rain (or snow) and how much. In terms of flash flooding, forecasting the occurrence and magnitude of such a high-impact precipitation event is a major challenge in operational meteorology. An important aspect to this challenge is the fact that it is, as put by Doswell (1996), a "concatenation of a meteorological event with a particular hydrological situation." The potential for rainfall to create a flash flood event depends on several factors such as antecedent precipitation and drainage basin characteristics. For instance, depending on the size or topography of the basin may influence the rate at which copious hail obstructs the basin. Although the hydrological aspects of flash flooding will not be discussed in this research work, they are definitely relevant to quantitative precipitation forecasting.

A physical understanding of why heavy precipitation occurs was developed by Doswell et al. (1996) through an ingredients-based approach. These ingredients were built upon a fairly simple concept wherein for any point on earth, $\mathbf{P} = \bar{\mathbf{R}}\mathbf{D}$, where $\mathbf{P}$ is the total precipitation, $\bar{\mathbf{R}}$ is the average rainfall rate, and $\mathbf{D}$ is the duration of the rainfall. Therefore, a high rainfall rate and/or a long duration of rainfall will result in a large precipitation accumulation. Despite the fact that significant precipitation is achieved through rising air that has considerable water vapor content and a rapid ascent rate, it is limited by how much water vapor ingested into a convective storm actually precipitates out. Accordingly, the instantaneous rainfall rate (**R**) is described as $\mathbf{R} = \mathbf{Ewq}$, where **E** is the precipitation efficiency, **w** is the ascent rate, and **q** is the mixing ratio of the rising air.

Regarding the duration of a rainfall event, it is expressed as $\mathbf{D} = \mathbf{L_s}(|\mathbf{C_s}|)^{-1}$, where $\mathbf{L_s}$ is the length of the system and $\mathbf{C_s}$ is the system motion vector. A long duration event would then be associated with systems that have slow movement and/or a great area of high rainfall rates along their motion vector. Furthermore, the convective cell movement ($\mathbf{C_c}$) and the propagation of the convective cells ($\mathbf{P_s}$) contribute to the motion of the system. The convective cell movement is generally driven by the mean wind ($\mathbf{V_m}$) in which the convective cloud is embedded, while propagation deals with the development and dissipation of individual convective cells. Collectively, slow system movement is characterized by weak winds, and the approximate cancellation of the cell movement through propagation effects (Fig. 2.14).

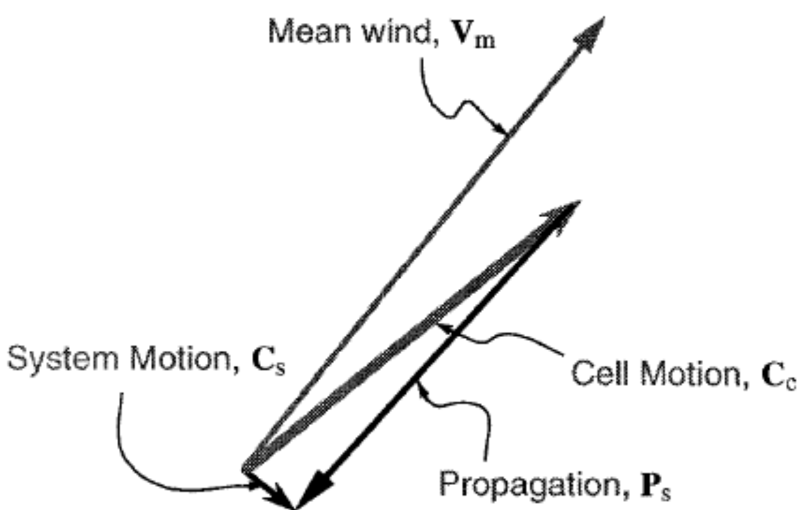


Fig. 2.14: Schematic showing the near cancellation between cell motion, C_c and propagation, P_s. From Doswell et al. (1996).

As suggested by Doswell et al. (1996), heavy precipitation can be associated with a range of storm types: multicells, supercells, squall lines, and mesoscale convective systems to name a few. In the perspective of heavy rainfall rates, the main characteristic of supercells is the strength of their updraft and the supply of low level moisture. Thus, applying the above ingredients for heavy precipitation to the severe convective event on 6 June, flash flood producing storms were likely given by the 1) supply of warm, moist air from the Southern Plains into the High Plains (buoyant instability), 2) sufficiently strong updrafts as estimated by the upward vertical velocities derived from the MLCAPE field (i.e. the maximum vertical velocity, $w_{max} = \sqrt{2CAPE}$; Markowski and Richardson, 2010), and 3) relatively weak steering flow (as indicated by the weak 500 hPa flow in the evening Denver sounding). Such characteristics would yield a relatively long duration event and high rainfall rate, illustrating the potential for slow-moving flash flood producing storms. For example, there were a couple local storm reports that described rainfall rates of 2.50 inches of precipitation over a two-hour period (see Fig. 2.15).

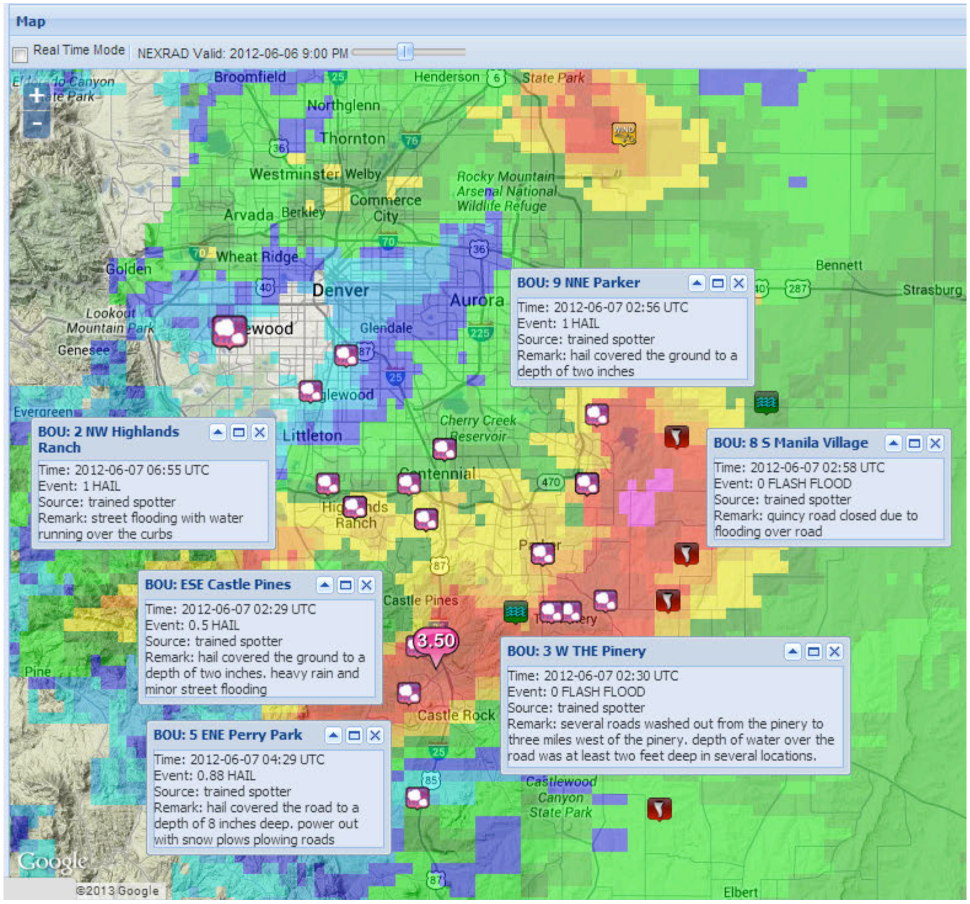


Fig. 2.15: Various local storm reports of hail and flash flooding in areas southeast of Denver, with radar reflectivity generally representing the storm activity around the report times.

Heavy rainfall was not the only hazard that led to flash flooding across the metropolitan areas of Denver and Colorado Springs; past studies have concluded that the lee of the Rockies is one of the primary areas in the United States for hail activity, especially in June (Changnon 1977, Schaefer et al. 2004, Cintineo et al. 2012). Out of the 96 total local storm reports from the Denver/Boulder and Pueblo WFOs, 73 of these reports were related to hail (moreover, several other reports also included some detail related to hail impacts). Most of these hail reports described 1.00 inch diameter hail or less (about 67%, smallest was 0.5 inches), while reports of hail greater than 1.00 inch were not as abundant (about 33%, biggest was 2.0 inches). Thus, a majority of the hail that fell from the convective storms were smaller in size, but of great quantity. Local storm reports of hail and flash flooding across the urban areas provided information on how heavy rains and hail (accumulating several inches deep on the ground) led to flooded streets and cars submerged under water (Figs. 2.15 and 2.16). The relatively high MLCAPE values across the eastern half of Colorado suggested the likelihood for hail, as it increased the potential for greater upward vertical velocities.

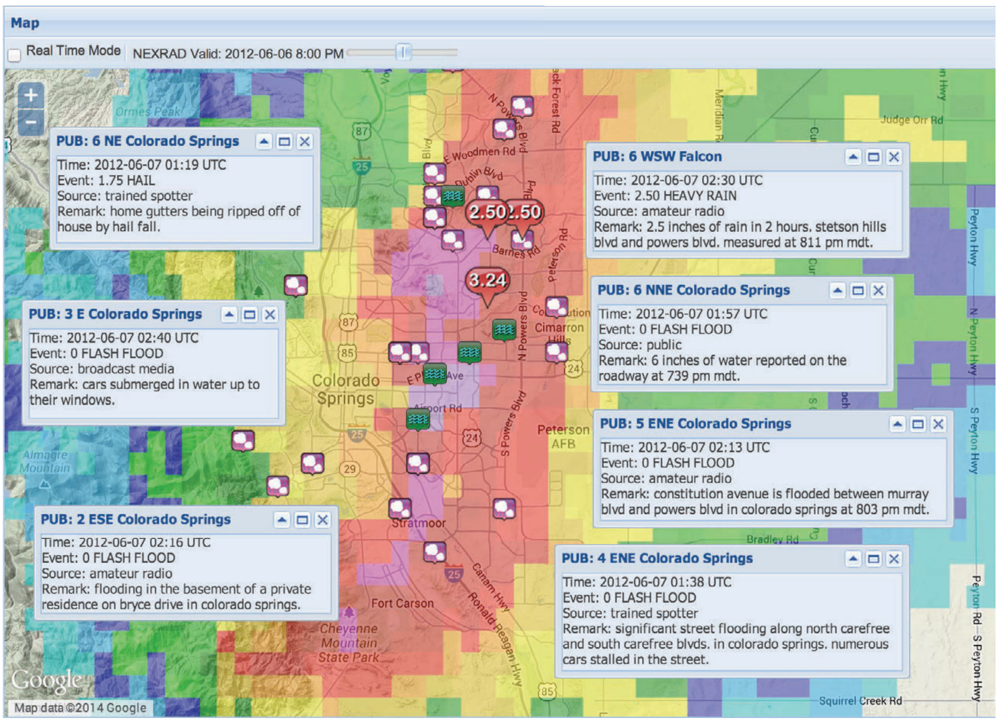


Fig. 2.16: Various local storm reports of hail and flash flooding in areas east of Colorado Springs, with radar reflectivity generally representing the storm activity around the report times.

The short time scales over which flood-producing rainfall happens (generally less than 6 hours) and the small spatial scales (generally less than 1000 km^2) of drainage basins in which flooding occurs differentiates flash floods from other types of flooding (Policy Statement, 2000). Considering the large quantity of quarter-sized hail falling over urbanized areas suggested that there was an increased risk for flash flooding given the 1) low permeability, 2) impervious ground surfaces, 3) sloped surfaces, and 4) potential congestion of small urban drainage basins. In addition, larger hailstones face a reduction in melting and evaporation rates compared to smaller hailstones (see van den Heever and Cotton 2004). There is an increased risk for precipitation runoff given the rapid melting associated with smaller hailstones. Furthermore, as more hailstones continue to fall and accumulate onto the surface, it is likely that drainage paths and culverts will become clogged, augmenting the potentials for flash flooding. Both the heavy precipitation and significant amounts of hail accumulating at the surface illustrate the “flash” nature and degree of damage with the severe convection on 6 June, especially for parts of Denver and Colorado Springs.

2.2.1 Surface precipitation analysis

To learn about and relate the location, spatial distribution, and quantity characteristics of precipitation from the 6 June severe convective event with radar reflectivity, the Stage IV precipitation analysis and LEVEL-II base radar data from the KFTG radar were utilized. This Stage IV dataset was retrieved from the regional 6 hourly multi-sensor precipitation analyses generated by the 12 River Forecast Centers over the continental United States. Furthermore, these analyses were derived from a combination of rain gauges and radar, and provided 6-hourly accumulated precipitation products. It is important to keep in mind that the Stage IV precipitation accumulation analyses are estimates of observed precipitation rather than exact measurements. This is because the instruments used to gather the data from provide approximations regarding the magnitude and distribution of precipitation. For example, while rain gauges provide ground-based measurements of precipitation, they cannot accurately represent the spatial extent as they are point estimates. Also, Doppler weather radars provide useful spatial and temporal resolution, but their coverage is inconsistent across the United States.

The LEVEL-II base data was retrieved from the National Climatic Data Center NEXRAD Data Inventory database.

The 24-hour Stage IV precipitation accumulation analysis, ending 1200 UTC 7 June, showed a widespread swath of precipitation throughout central and northeast Colorado, as well as into southeast Wyoming (Fig. 2.17). The heaviest amounts of precipitation fell near several metropolitan areas, such as the city of Cheyenne, Denver and Colorado Springs. These areas received over 50 mm (2 inches) of precipitation, with smaller local areas receiving more than 100 mm (4 inches) of precipitation. The highest precipitation estimate was approximately 148 mm (about 6 inches) south and southeast of Denver in central Arapahoe County. Assessing the 24-hour period of precipitation in 6-hour intervals revealed some unique insights into how the behavior of convection played a role in patterns of precipitation seen in the Stage IV precipitation accumulation analyses.

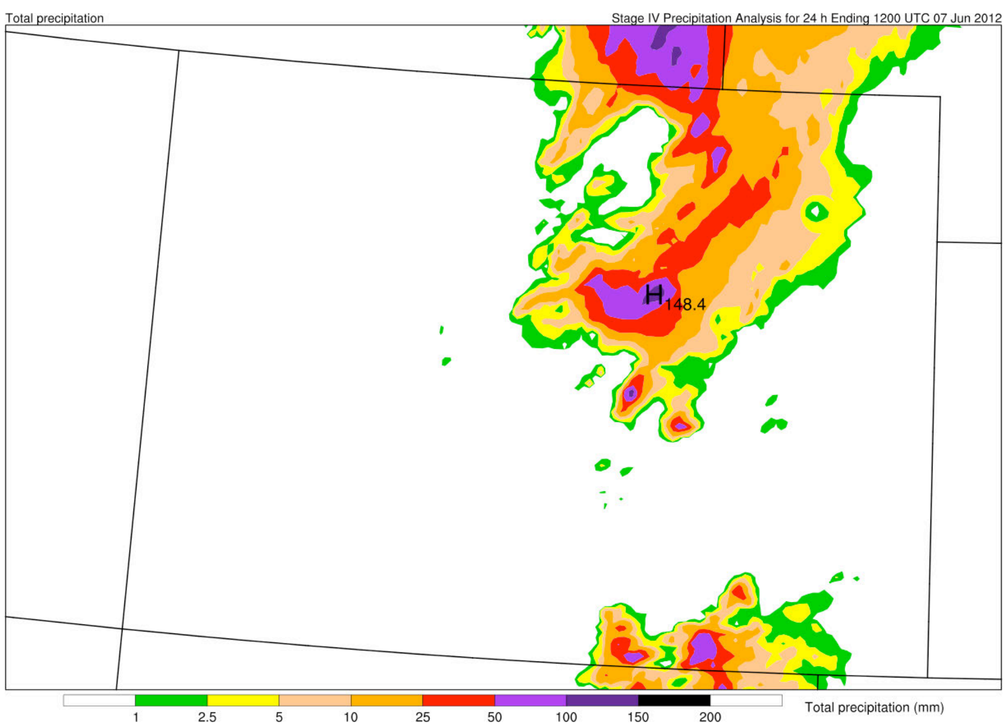


Fig. 2.17: 24-hour Stage IV precipitation analysis ending on 1200 UTC 7 June 2012.

As convection began to initiate at approximately 2100 UTC 6 June and spread south and west along the convergence boundary, precipitation began to accumulate in the early evening in a similar pattern. The 6-hour Stage IV precipitation accumulation analysis, ending at 0000 UTC 7 June, showed a path of precipitation extending from Cheyenne, Wyoming south to Centennial, Colorado (Fig. 2.18a). Within this path of precipitation were a couple local areas that had received over 100 mm (2 inches) of precipitation. This suggested that within this evening convection were some heavy rain producing thunderstorms, as illustrated by the high reflectivities in the radar imagery on 2327 UTC 6 June (Fig. 2.18b). This makes sense given the advection of warm, moist air from the southeast feeding into the convection. In addition, the radar imagery also depicted back-building convection, in which case areas already soaked from the first round of thunderstorms generated off the convergence boundary were hit again.

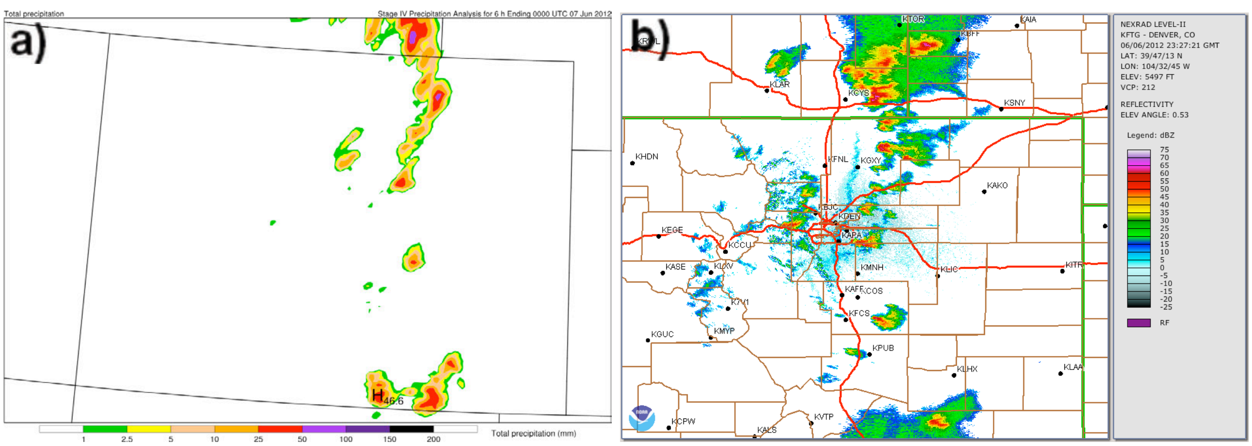


Fig. 2.18: (a) 6-hour Stage IV precipitation analysis ending on 0000 UTC 7 June 2012.
(b) KFTG radar reflectivity depicting the high reflectivities and backbuilding convection at approximately 2327 UTC 6 June 2012.

2.2.2 Particular convective cell characteristics

Attention herein is given to the storm cell southeast of Denver and east of Colorado Springs, as convection continued to build, strengthen, and propagate towards the west and southwest throughout the evening (Fig. 2.19). The convective cell east of Colorado Springs in El

Paso County did not begin to develop until after 0000 UTC 7 June (Fig. 2.19b). It is hypothesized that the southwest propagation characteristics of both the Denver and Colorado Springs storm cells were likely as a result of a southwest moving convective outflow boundary (produced from the existing convective cells) interacting with the Front Range terrain and promoting easterly moist upslope flow (Fig. 2.20). The stationary nature of the convective cells due to weak steering flow aloft (as previously discussed) allowed the cells to continuously precipitate within the same vicinity of initial development. Additionally, the continuous advection of warm, moist air from the southeast contributed to their sustenance throughout the evening. It was not until 0300 UTC 7 June that the storm cell southeast of Denver began to show signs of slight dissipation (yet, was still precipitating over the same vicinity) and the storm cell near Colorado Springs had moved further east (Figs. 2.19c, d). On another note, new convection began to develop over northern portions of the foothills, likely due to moist, southeasterly upslope flow.

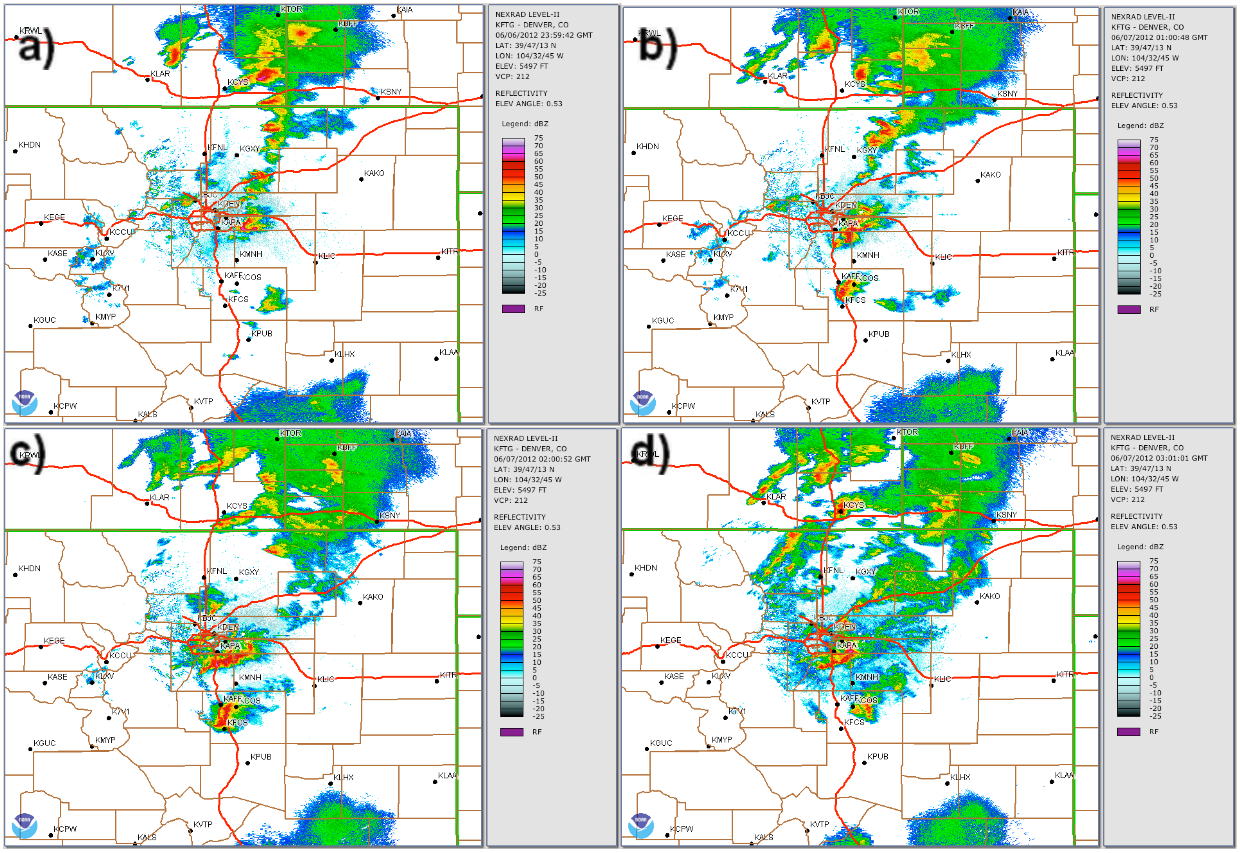


Fig. 2.19: KFTG radar reflectivity at approximately (a) 2359 UTC 6 June 2012, (b) 0100 UTC 7 June 2012, (c) 0200 UTC 7 June 2012, and (d) 0301 UTC 7 June 2012.

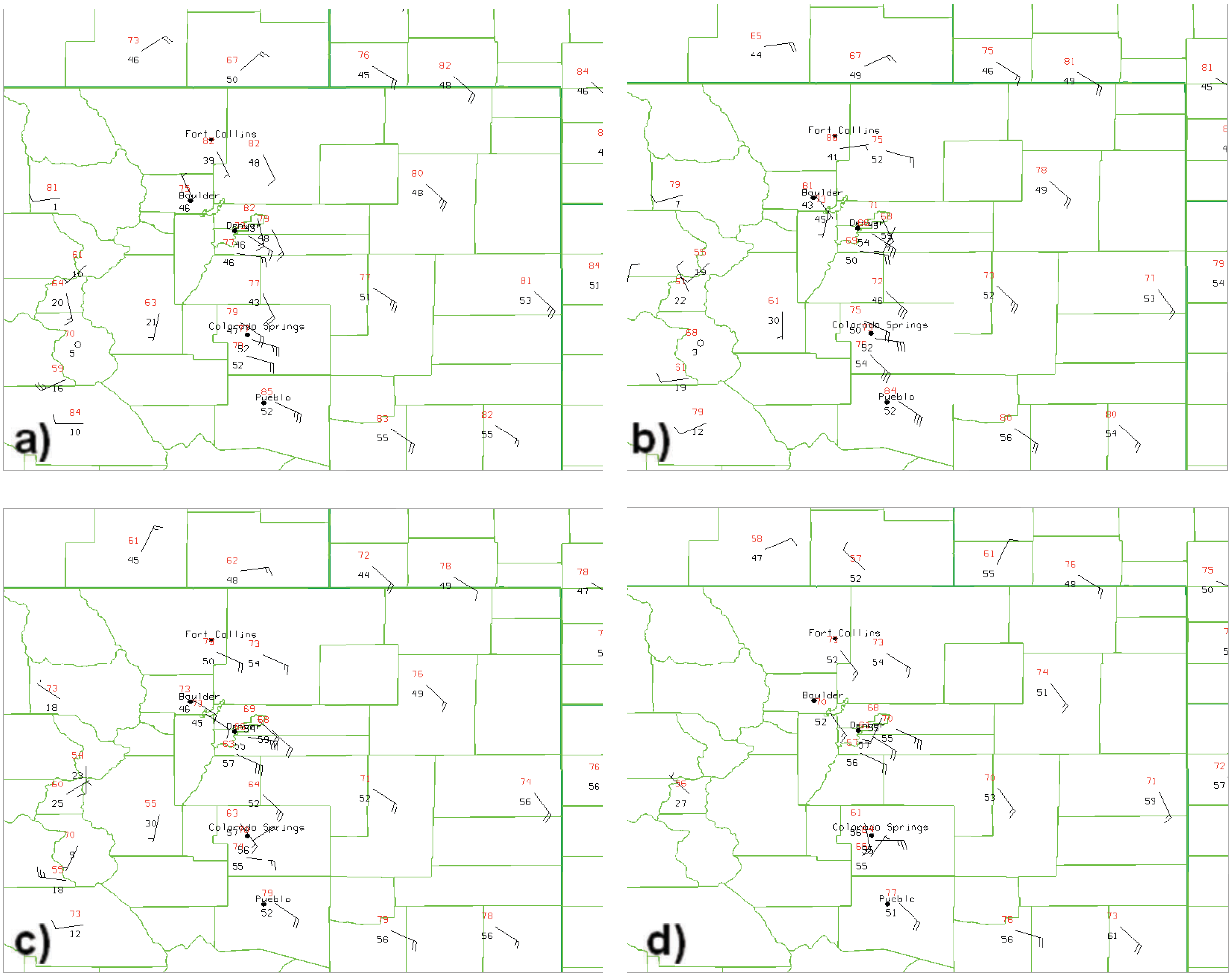


Fig. 2.20: Surface METAR observations at (a) 0000 UTC 7 June 2012, (b) 0100 UTC 7 June 2012, (c) 0200 UTC 7 June 2012, and (d) 0300 UTC 7 June 2012.

The stationary nature of these storm cells had produced an apparent impact in the precipitation accumulations received that evening, as emphasized in Fig. 2.21. The 6-hour Stage IV precipitation analysis, ending at 0000 UTC 7 June, showed three primary areas of heavy precipitation, all of which were near metropolitan areas. There was a precipitation maximum just east of Colorado Springs, where over 130 mm (over 5 inches) of precipitation was estimated to have fallen within that 6-hour period. To its north, there is a second precipitation maximum southeast of Denver, with over 50 mm (2 inches) of precipitation. The northern most precipitation maximum near Cheyenne, Wyoming resulted in over 120 mm (~5 inches) of precipitation. Slow moving convection off the Cheyenne Ridge was likely the cause for such a high precipitation accumulation.

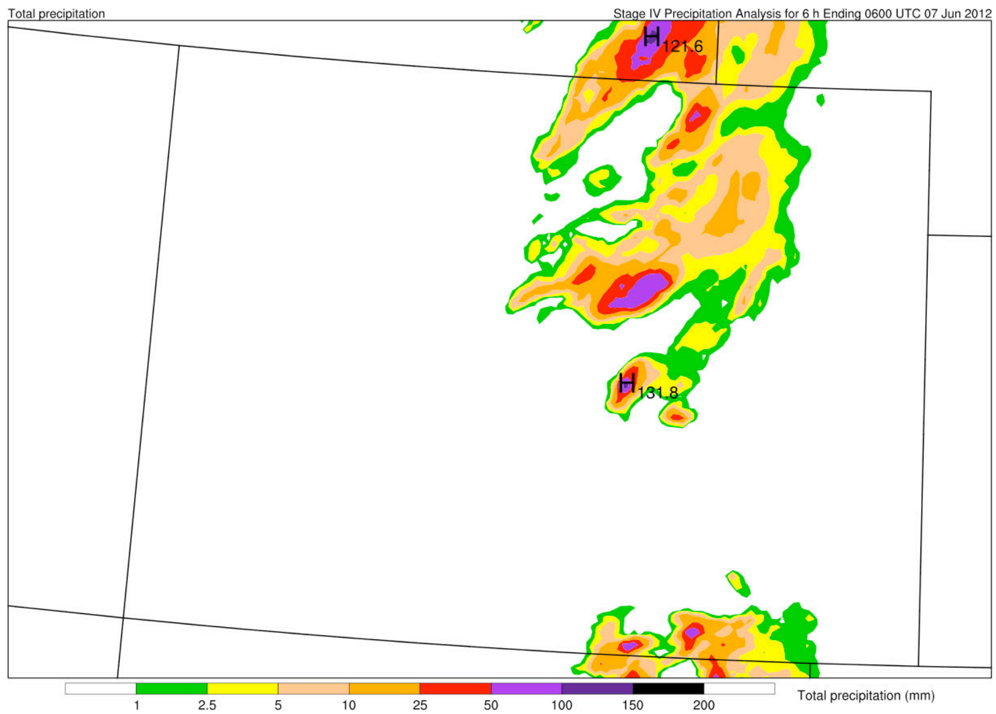


Fig. 2.21: 6-hour Stage IV precipitation analysis ending on 0600 UTC 7 June 2012.

While the storm cell east of Colorado Springs dissipated as it moved east and northeast through the night, stratiform precipitation had spread across the High Plains (Fig. 2.22a). Interestingly, the convection south and east of Denver continued to persist despite its slight decrease in intensity. This persistence may be due to a combination of moist upslope flow and outflow boundaries interacting with the terrain to initiate new convection. Eventually, this area of convection was joined by other convection that had developed off the foothills and was moving east (Fig. 2.22b). This enhanced convection then slowly moves northeast as it expands and decreases in intensity (Fig. 2.22c). The precipitation associated with this overnight convection is illustrated by the 6-hour Stage IV precipitation accumulation analysis, ending 1200 UTC 7 June (Fig. 2.22d). Denver had received a little over 55 mm (~ 2 inches) of precipitation, which is in addition to the precipitation that had already fallen throughout the evening. The path of the overnight convection is evident by the swath of precipitation extending from Denver northeast towards Sterling, with precipitation amounts exceeding 25 mm (1 inch).

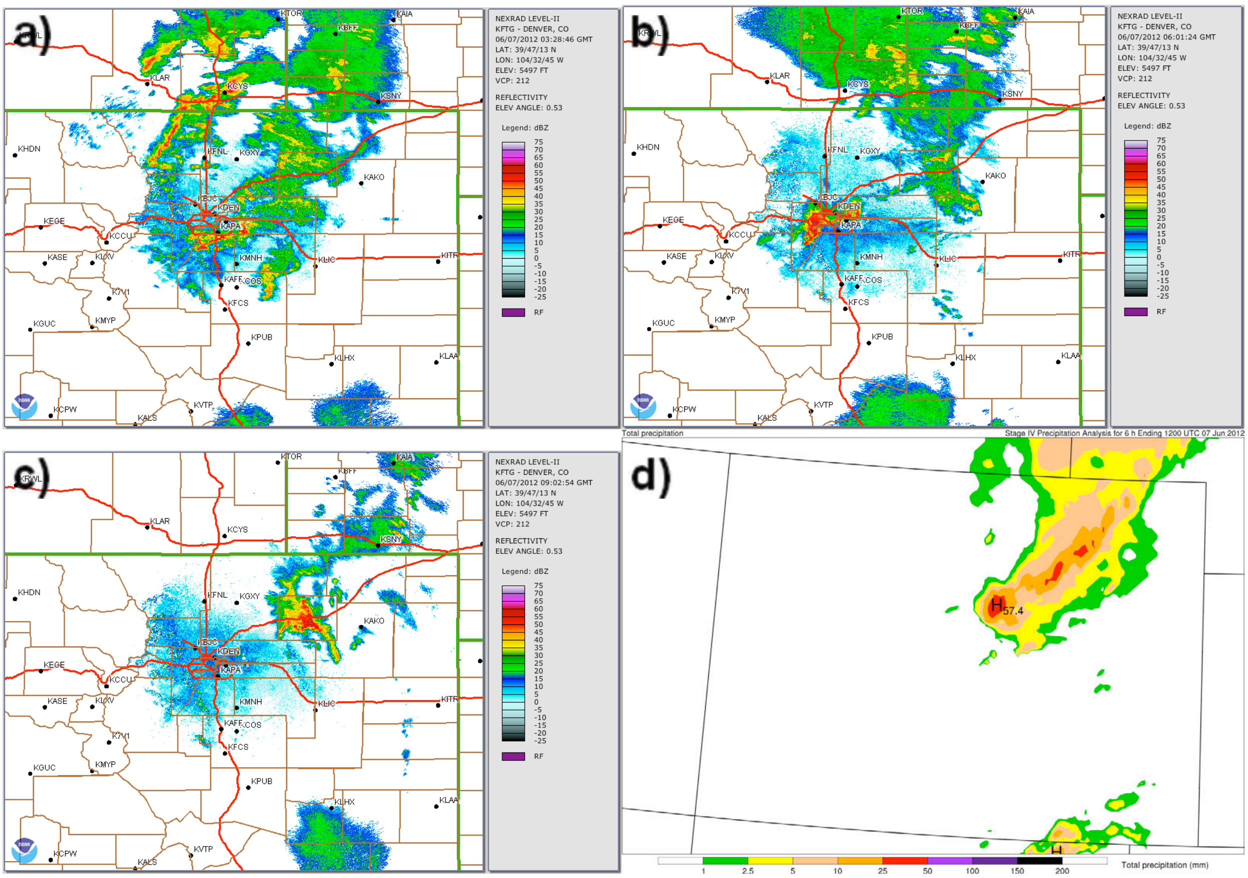


Fig. 2.22: KFTG radar reflectivity at approximately (a) 0325 UTC 7 June 2012, (b) 0601 UTC 7 June 2012, and (c) 0902 UTC 7 June 2012. (d) 6-hour Stage IV precipitation analysis ending on 1200 UTC 7 June 2012.

The precipitation characteristics in the 24-hour Stage IV precipitation accumulation analysis (ending 1200 UTC 7 June, Fig. 2.17) corresponded reasonably well with the 24-hour precipitation accumulation (ending 1300 UTC 7 June) observations reported by numerous weather observers as part of the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network (Fig. 2.23). As shown in the CoCoRaHs daily precipitation report, the hardest hit areas from the convection on 6 June included Denver County, northeastern Douglas County, and western El Paso County. Reports of 0.50 inches to 3.00 inches of precipitation were spread across the city of Denver and into areas northeast of Castle Rock, with a couple reports of 3.00 inches to 5.00 inches of precipitation. This area of heavy precipitation was estimated well by the Stage IV precipitation analysis, given the range of 25 mm (1 inch) to 150 mm (6 inches) of precipitation to the southwest of Denver. The CoCoRaHs daily precipitation report also showed a variety of precipitation observations near Colorado Springs, anywhere from 0.25 inches to about 4.50 inches. The Stage IV analysis estimated this area of precipitation well with a range of precipitation from 25 mm (1 inch) up to 150 mm (6 inches).

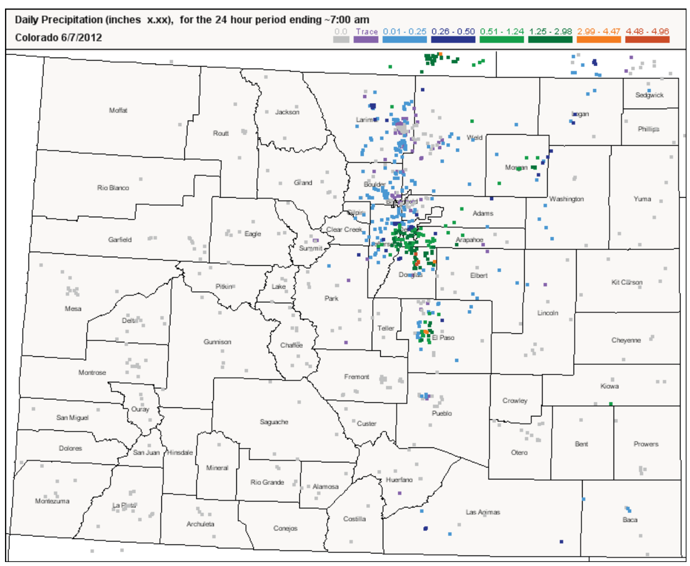


Fig. 2.23: 24-hour precipitation observations, ending at 1300 UTC 7 June, reported by numerous Community Collaborative Rain, Hail and Snow (CoCoRaHS) network observers.

Throughout the discussion regarding the meteorological processes that took place on 6 June 2012, several uncertainties arose concerning the exact mechanisms responsible for convective initiation and the anomalous storm cell motion near the city of Denver and Colorado Springs. Was the initial development of convection as a result of the cold front passage instead?

What drove the boundary westward? What was the primary factor for the storm motion observed with the Denver and Colorado Springs convective cells? Was it the outflow boundaries, upslope flow or a combination of the two that contributed to the propagation of the system and perhaps slow system movement? These are the types of questions that motivate this research work into using an ensemble prediction system to seek answers. The goal is to illustrate the resourcefulness of ensembles in validating the theories and clarifying any possible ambiguity presented in this case study, as well as highlighting the practicality of its forecasts.

CHAPTER 3

PERFORMANCE OF CONVECTION-ALLOWING AND CONVECTION-PARAMETERIZED ENSEMBLE FORECASTS

3.1 Ensemble forecasting

In a sense, probabilistic forecasting reflects our familiarity concerning the behavior of our atmosphere and our ability to use numerical weather prediction for the purpose of weather forecasting. Ensemble prediction systems are designed to capture the probabilities for weather events and the range of uncertainty that is inherent in each forecast situation it generates. There is great value in examining a set of multiple forecasts not only to identify the range of possible weather scenarios, but also to help determine the probability of specific high-impact forecast outcomes such as heavy precipitation. Forecasting warm season precipitation events is difficult due to the small-scale and chaotic nature of deep, moist convection (e.g. Carbone et al. 2002, Davis et al. 2003). Intuitively, this challenge is particularly exacerbated in areas with variation in topography such as those in the western United States. The warm season convective event that occurred within the Front Range and High Plains of Colorado on 6 June 2012 represents a scenario that incorporates the mesoscale and geographic challenges in forecasting convection.

This study makes use of ensemble forecasts as an evaluation tool to determine: 1) how well the ensemble was able to resolve the mesoscale features responsible for the convection on the evening of 6 June 2012, 2) the degree of uncertainty within these forecasts in relation to precipitation estimates, and 3) how illustrating that uncertainty within various forecast representations is understood by Front Range decision makers. The ensemble system is composed of different model runs all having slightly different initial conditions, essentially providing a collection of possible weather scenarios. Accordingly, the uncertainties and probabilities of the forecasts may be assessed.

3.1.1 Data assimilation configurations

Two key components were used in this study to assimilate the observations and generate the initial conditions necessary for the ensemble system: a mesoscale model and a data assimilation package. The characteristics of the data assimilation and ensemble configurations are similar to those described by Schumacher and Clark (2013, in review). The investigators in this study generated probabilistic precipitation forecasts for a series of heavy-rain-producing mesoscale convective systems using four different convection-allowing ensemble configurations. Two of these configurations involved continuously cycling data assimilation, each of which ran with both a single set of physics parameterizations and a mixture of physics parameterizations. Similar procedures are applied to the ensemble methods presented herein, although using various physics parameterizations were not considered in the ensemble design. Furthermore, plans for the ensemble analysis were expanded to include forecast results from a convection-parameterized ensemble as well.

The Advanced Research version of the Weather Research and Forecasting model (WRF-ARW; Skamarock et al. 2008), version 3.4.1, was used to generate a forecast of the warm season severe convective event on 6 June. It is a nonhydrostatic mesoscale model that is fully compressible, with a terrain-following hydrostatic pressure vertical coordinate system. The forecast was initialized on 0000 UTC 6 June and was simulated for a 48-hour period, ending on 0000 UTC 7 June. Regarding assimilation, the WRF-Data Assimilation Research Testbed (WRF-DART; Anderson et al. 2009) was an integral method considered in this study to construct two different ensemble systems using an effective ensemble adjustment Kalman filter (EAKF) that produces small assimilation errors (see Anderson 2001). Past studies have integrated this data assimilation package in some way for producing short-range mesoscale forecasts of various phenomena, concluding reasonable results. For example, Yussouf et al. (2013) used the EAKF in their combined mesoscale and storm scale ensemble data assimilation system to generate a short range ensemble forecast of the 8 May 2003 Oklahoma City tornadic supercell. The initialization and movement of the supercell storm was represented with good accuracy in the model. A similar study conducted by Yussouf et al. (2013) investigated the impact of fixed and multiple model physics on probabilistic forecasts of supercell storms produced by a mesoscale ensemble, also using the EAKF within WRF-DART. Forecasts of surface fields and significant tornado parameters were well represented by the ensemble system with multiple physics. The Schumacher and Clark (2013, in review) study found that the best precipitation forecasts came from the ensemble also using a mixture of physics parameterizations and a shorter assimilation cycle. These past studies illustrate the quality of results retrieved from incorporating a data assimilation package such as WRF-DART in an ensemble forecast study.

First, a 24-member convection-allowing ensemble forecast was generated of this severe weather event using a high resolution model domain. In this ensemble configuration, the cumulus parameterization option was turned off for all members given that a convection-allowing simulation was sufficient to explicitly represent convection due to its higher resolution characteristics (e.g. Weisman 1997, Done et al. 2004). Second, a 24-member convection-parameterized ensemble forecast was produced, in which case the cumulus parameterization option implemented for all members was the Tiedtke scheme (Tiedtke 1989, Zhang et al. 2011). Both ensembles were ran at a 36 km horizontal grid spacing during the data assimilation process on a domain encompassing North America, as well as portions of the eastern (western) Pacific (Atlantic) Oceans (Fig. 3.1). The purpose of extending off the western United States and into the Pacific Ocean was to be considerate of the synoptic-scale weather systems coming onto the mainland and influencing the information fed into the inner domain.

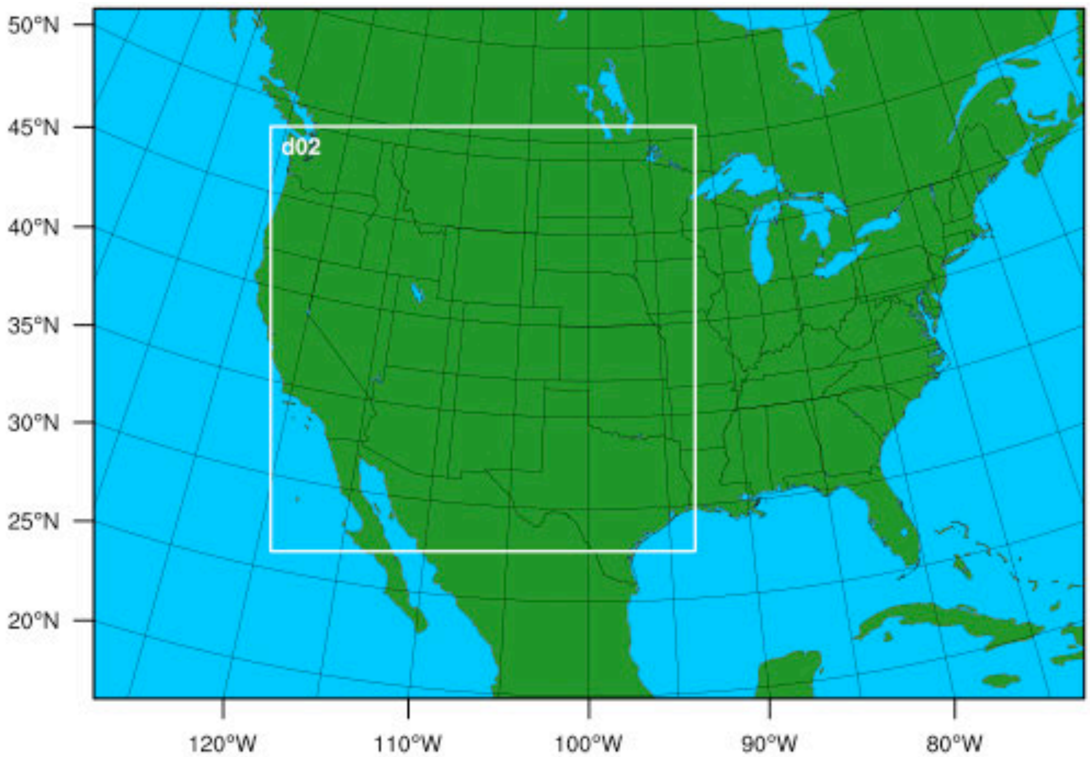


Fig. 3.1: Outer and inner domain (d02) used by data assimilation and WRF ensemble system.

The configurations for both the convection-allowing and convection-parameterized ensembles used continuously cycled data assimilation through the WRF-DART system. This process began at 0000 UTC 3 June 2012, that is, the beginning of the 3-day period prior to the initialization time of the ensemble forecast. As in Schumacher and Clark (2013, in review), these ensemble assimilations were initialized with the 36-hour Global Forecast System (GFS) forecast retrieved from the National Climatic Data Center's National Operational Model Archive & Distribution System (NCDC NOMADS). This GFS forecast was valid at 0000 UTC 3 June.

It was also perturbed using a stochastic process from the National Center for Environmental Prediction (NCEP) background error covariance using the WRF data assimilation system to produce a realistic set of initial condition fields to use in the ensemble system (see Barker et al. 2012). Furthermore, the perturbation method was only applied at the start of the initialization time of the ensemble forecast.

What characterizes an ensemble prediction system is the fact that it generates a set of plausible forecasts using perturbed initial and lateral boundary conditions (LBCs). Thus, the perturbed 36-hour GFS forecasts were also used by the WRF-DART system as LBCs. In this case, the fixed covariance perturbation method was utilized (see Torn et al. 2006). Throughout the assimilation cycle, the perturbations were applied every 6 hours. In relation to observational data, standard observations from the NCEP Global Data Assimilation System (GDAS) were assimilated into the perturbed GFS forecasts by the WRF-DART system. This included observations from the surface, upper-air radiosondes, ships, and satellites to provide a few examples.

3.1.2 Convection-allowing and convection-parameterized ensemble configurations

The WRF-DART package is a tool integrated in this study to generate forecasts from a convection-allowing and a convection-parameterized ensemble system in order to assess their performance in forecasting a warm season convective event. Although using coarse grid spacing and convective parameterizations is the more cost-effective option in generating convective precipitation forecasts, they are unable to sufficiently represent important small-scale processes. Clark et al. (2009) has observed improvements in rainfall forecasts over the central United States by comparing ensemble systems using both explicit and parameterized representations of convection, finding that the ensemble with higher resolution generated more accurate and reliable forecasts. It was of interest to determine whether or not a similar outcome would follow the ensemble analysis of the 6-7 June 2012 Front Range severe convective event. It is hypothesized that there may be less of a significant difference between the precipitation forecasts generated by both ensembles given the mountainous terrain influences.

Each ensemble generated a 24-member, 48-hour forecast, initialized at 0000 UTC 6 June 2012. Specifically, the convection-allowing (convection-parameterized) ensemble was run on a 4 km (12 km) horizontal grid spacing domain covering much of the United States west of the Mississippi River up to the western coast (denoted as d02 in Fig. 3.1). The character of this domain was purposely chosen to focus on forecasted weather events in the western United States, with primary attention given to the state of Colorado and surrounding areas. As the case study presented in this research work takes place in a region influenced by varying terrain, it was important to consider orographic features when delineating the inner domain.

Both the convection-allowing and convection-parameterized ensembles were initialized on their single inner domain of corresponding grid spacing by downscaling the WRF-DART analysis to those inner grids. The same model configurations from their parent assimilation system were used. The only differences were the smaller grid spacing and domain. Also, in the convection-allowing ensemble, cumulus convection was explicitly resolved (rather than parameterized as in the convection-parameterized ensemble). The LBCs used for both the 4 km and 12 km inner domains were obtained from the GFS forecast initialized 6 hours prior to the start of the ensemble forecast (1800 UTC 5 June 2012), and were collected out to 54 hours (thus, covering the period from 1800 UTC 5 June to 0000 UTC 8 June). These LBCs were also perturbed using the same fixed covariance perturbation method as before.

In summary, to produce a realistic set of initial condition fields for use in both ensemble systems, the cycling of assimilation involved perturbing the 36-hour forecast that was valid at the beginning of the 3-day period prior to the initialization time of the ensemble forecast. That is, the 36-hour perturbed forecast is valid on 0000 UTC 3 June 2012. Standard observations are then assimilated into the perturbed forecast. The forecast file is then simulated for the next 6 hours, assimilated with a new set of observations, simulated for another 6 hours, and this process is repeated until the time stamp is equal to that of the initialization time of the ensemble model. The initialization file is then downscaled to the appropriate inner grid and prepared for use in the ensembles. For more detailed information regarding model configurations, see Table 3.1.

Table 3.1: Details of the various configurations considered in the WRF-ARW ensemble set-up.

Model Configurations	WRF-ARW 4-km and 12-km Ensemble Forecasts
Boundary Layer	Mellor-Yamada-Janjic scheme
Microphysics	Morrison 2-moment scheme
Land surface	Noah
Cumulus Parameterization	4-km = none, 12-km = Tiedtke scheme

3.2 Evaluation methods for convection-allowing and convection-parameterized forecasts

To evaluate the overall performance of both the convection-allowing and convection-parameterized ensemble forecasts, modeled radar reflectivity was compared to the LEVEL-II base data from the KFTG radar. Also, modeled precipitation was compared to the Stage IV precipitation analyses. A variety of aspects were considered in this assessment of ensemble performance: the source, timing, and location of convective initiation; the evolution of convection; the ability to adequately resolve observed mesoscale features; and the amount and spread of precipitation.

To distinguish between the ensemble members that captured the meteorological processes related to the 6 June severe convective event well from those that did not, two approaches were considered. The first approach was subjective in which case the 24-hour accumulated precipitation forecast from each ensemble member was compared to the Stage IV 24-hour accumulated precipitation analysis. A "good" rating was given to those members that were able to forecast the spread and magnitude of precipitation, as well as the location of precipitation maxima, relatively well to what was observed. On the contrary, a "poor" rating was given to those members that completely underestimated the amount of precipitation, as well as displaced the spread of precipitation and precipitation maxima.

To further validate and funnel down these subjectively-chosen ensemble members, a verification method adopted from Roberts and Lean (2008) was used to determine the skill of their precipitation forecasts at various thresholds. This verification tool, known as the Fractions Skill Score (FSS), served as the objective approach to compare how well the forecasts represented the observed. The FSS can be defined as

$$\mathrm{FSS}_{(n)} = \frac{\mathrm{MSE}_{(n)} - \mathrm{MSE}_{(n)\mathrm{ref}}}{\mathrm{MSE}_{(n)\mathrm{perfect}} - \mathrm{MSE}_{(n)\mathrm{ref}}} = 1 - \frac{\mathrm{MSE}_{(n)}}{\mathrm{MSE}_{(n)\mathrm{ref}}},$$

where $\mathbf{MSE}_{(n)}$ is the mean square error for the observed and forecast fractions from a neighborhood of length n and $\mathbf{MSE}_{(n)\mathrm{ref}}$ is the largest possible mean square error that can be retrieved from both the forecast and observed fractions (see Roberts and Lean 2008, section 2).

Analyzing the magnitude and spatial characteristics of precipitation, as well as the FSS, to distinguish between the "good" and "poor" ensemble members is a method that has been similarly used by past studies. For example, Lynch and Schumacher (2012) identified the most accurate and least accurate ensemble member forecasts through studying the spatial distribution of precipitation, verification scores, and multiple meteorological fields. Assessing multivariate fields is a method suggested by Roulston and Smith (2003) in order to identify the best member, as the likelihood for any ensemble member to match verification exactly is improbable. The FSS were computed using version 4.0 of the Meteorological Evaluation Tools (MET; http://www.dtcenter.org/met/users/index.php) package.

The FSS was determined by calculating the fraction of grid points exceeding a given threshold in both the forecasted and radar-observed rainfall. Then, for every grid point, this calculation was repeated for neighborhoods of 13 by 13 grid points. This process demonstrates the direct relationship between the FSS and the size of the neighborhood, where skill increases with increasing neighborhood size. An equal number of observed and forecast grid points exceeding the threshold would result in a FSS of 1, that is, a forecast with perfect skill whereas a score of 0 indicates no skill (Fig 3.2). The ensemble members that were subjectively recognized in forecasting the 24-hour accumulated precipitation well (poorly), and were closest to an FSS score of 1 (0), were designated as a “good” (“poor”) ensemble member.

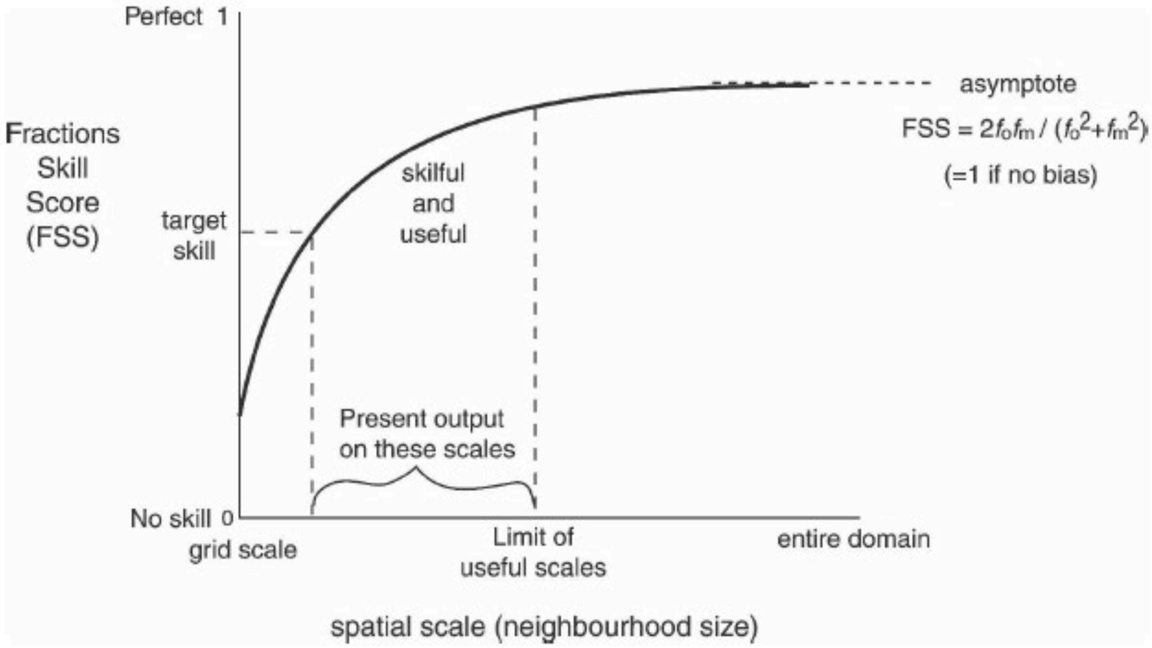


Fig. 3.2: Schematic graph of forecast skill against spatial scale. From Roberts and Lean (2008).

It is important to note that the subjective approach was applied to both the convection-allowing and convection-parameterized ensemble forecasts, whereas the objective approach was only applied to the former. As will be discussed in the next section, the convection-allowing ensemble precipitation forecasts outperformed those from the convection-parameterized ensemble. As a result, further analysis was dedicated towards studying the mesoscale features resolved by the convection-allowing ensemble, and how those features played a role in its precipitation forecasts.

Once the subgroup of "good" and "poor" ensemble members were selected from the convection-allowing ensemble, deeper study was given into what meteorological features were reasonably resolved or challenging to resolve, and how those successes or difficulties influenced the precipitation forecasts drawn from the ensemble members. Simulated radar reflectivity, streamlines, surface temperature and dewpoint 2 m above ground, and precipitation were the fields use to characterize the forecast abilities of the ensemble members in the subgroup.

3.2.1 Results and discussion of ensemble system performance

3.2.1a Forecasting convection

The convection-allowing and convection-parameterized ensemble forecasts were evaluated between the time period of 1200 UTC 6 June and 1200 UTC 7 June 2012 in terms of how well they forecasted the initiation and progression of the convective activity on the evening of 6 June. At 1200 UTC 6 June, no significant weather was occurring at the time over the state of Colorado. Most, if not all, of the members from both ensemble sets forecasted a quite morning for Colorado as well.

By noon, the KFTG Denver radar showed some indication of a developing convergence boundary, although there was yet no convective initiation along or anywhere near the boundary (Fig. 3.3). On the contrary, at least 50% of the convection-allowing ensemble members were already showing signs of convection beginning to develop in extreme northeast Colorado and into the Nebraska panhandle area (Fig. 3.4). Meanwhile, nearly all of the convection-parameterizing ensemble forecasts showed no initial convective activity until approximately 2200 UTC 6 June over the foothills (not shown). In reality, convection did not begin to develop until approximately 2100 UTC, at least along the northern edge of the convergence boundary (Fig. 2.8b). For areas in extreme southeast Wyoming, convection began a half an hour earlier (not shown). These observations suggest that not only did the convection-allowing ensemble members generate an early onset for convective initiation, but they also had an eastward bias in forecasting the initial convection. On another note, the convection-parameterized ensemble forecasts represented the morning and early afternoon weather activity fairly well thus far, initiating convection slightly later than what was observed.

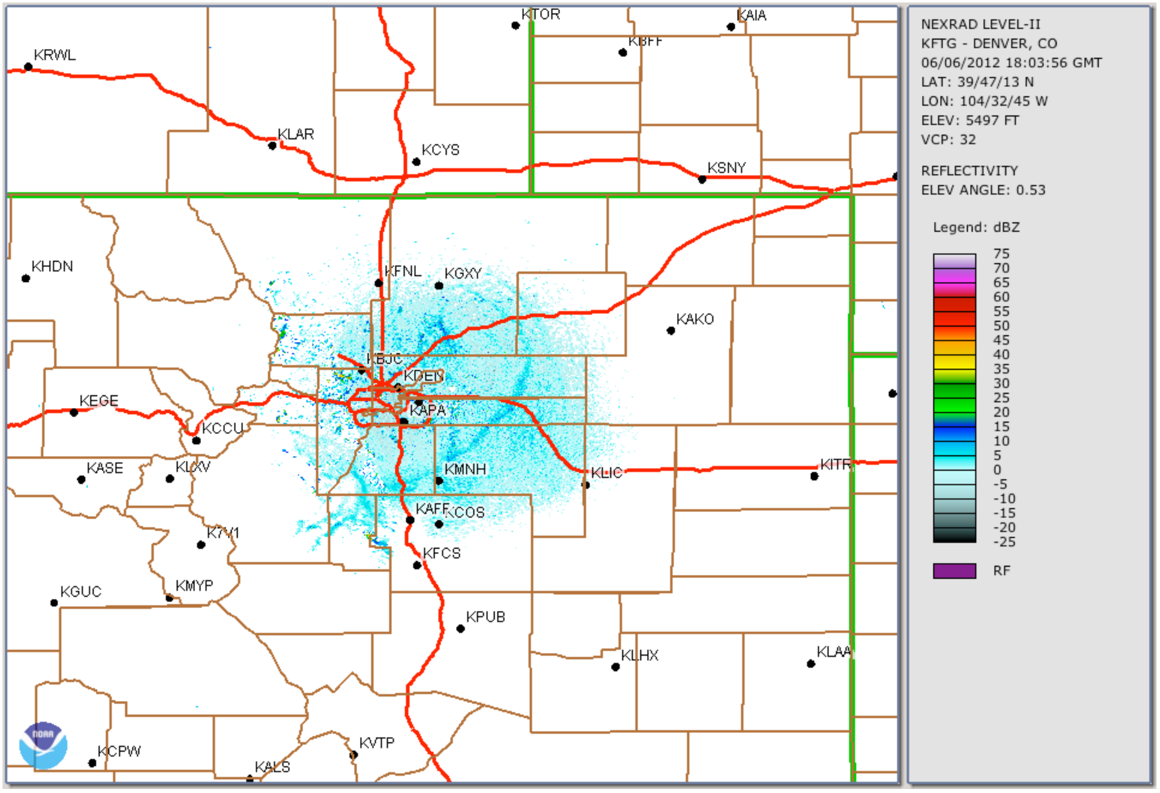


Fig. 3.3: KFTG radar reflectivity at approximately 1804 UTC 6 June 2012.

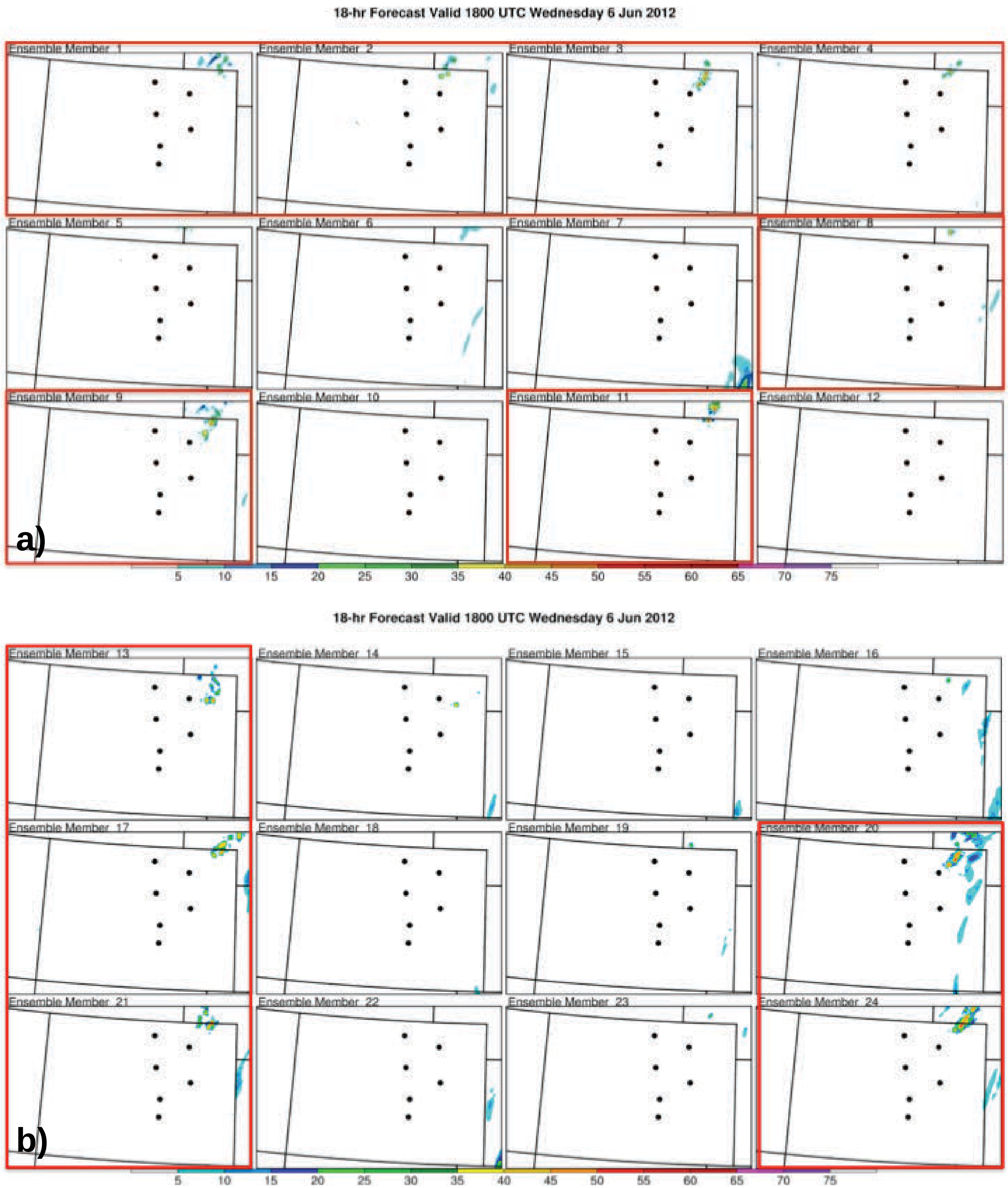


Fig. 3.4: Convection-allowing ensemble forecast of radar reflectivity valid at 1800 UTC 6 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.3 and Table 4.1). Red boxes highlight those particular members that showed signs of initial convective activity.

As time progressed into the early evening hours, convection continued to build in southeast Wyoming in a northeast to southwest fashion (Figure 3.5a). Meanwhile, as the convergence boundary moved westward towards the foothills, convection continued to build south and west along the boundary (Figs. 3.5). It was not long before some minor convective activity also began to develop over the foothills area nearing 2300 UTC (Fig. 3.5b). In a general sense, a majority of the convection-allowing ensemble members continued to 1) build convection south and west, extending from northeast Colorado or the Nebraska panhandle, and 2) began to initiate convection along the foothills (Fig. 3.6). Given that the convection-allowing ensemble had a "head start" in producing the initial convective activity on 6 June, it is not a surprise that its members had an early onset for the convection along the foothills as well. In relation to the convection-parameterized ensemble, a majority of the members forecasted convective initiation primarily over and to the lee of the foothills (Fig. 3.7). In some cases, convection was also forecasted to develop somewhere in the region traced by connecting the locations of Fort Collins, Denver, Limon, and Fort Morgan (reflectivity ≥20 dBz). Given these observations, it seems as though the convection-allowing ensemble organized its initial convection more or less along where the convergence boundary was observed, while the convection-parameterized ensemble focused more near the foothills.

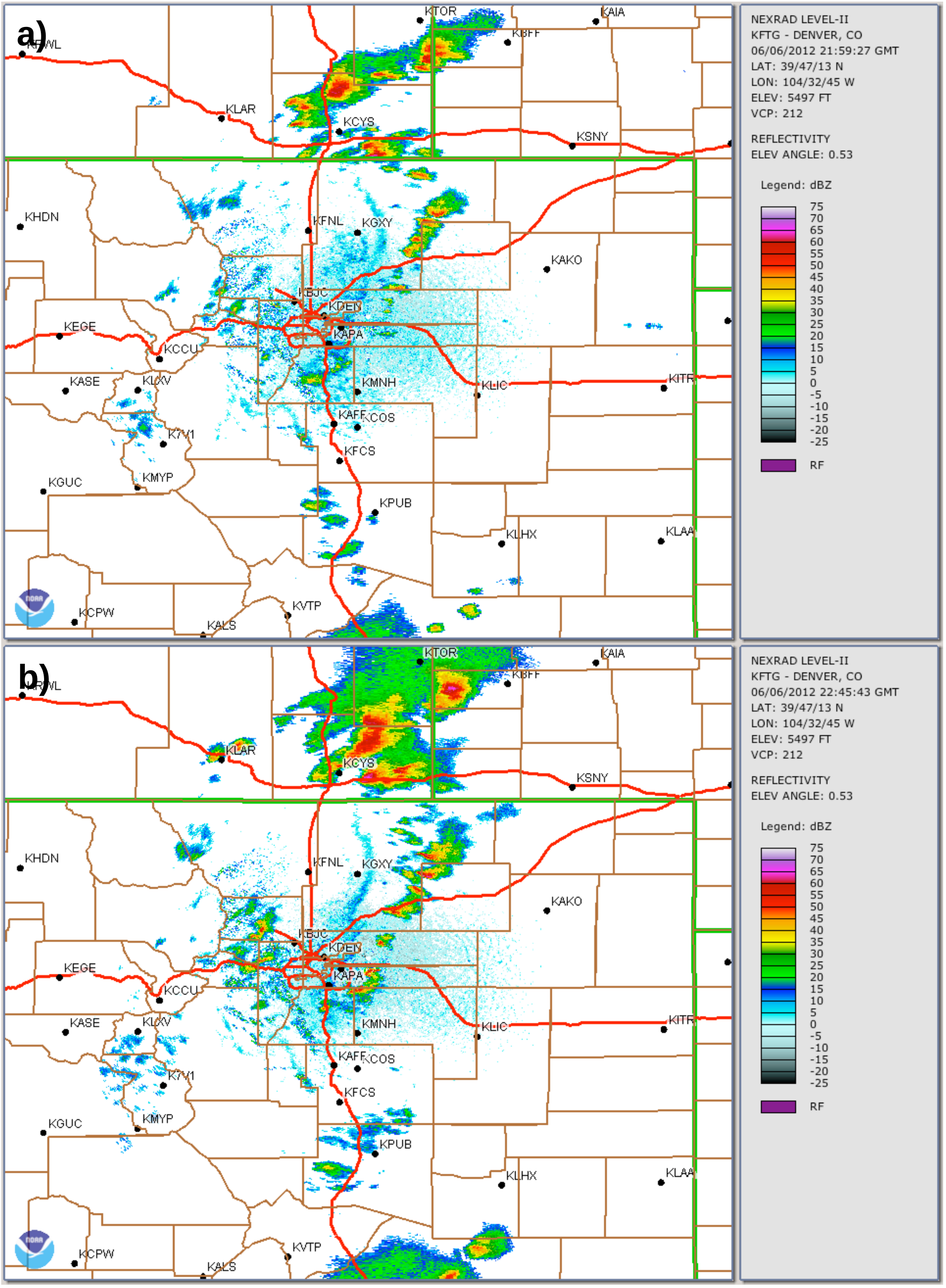
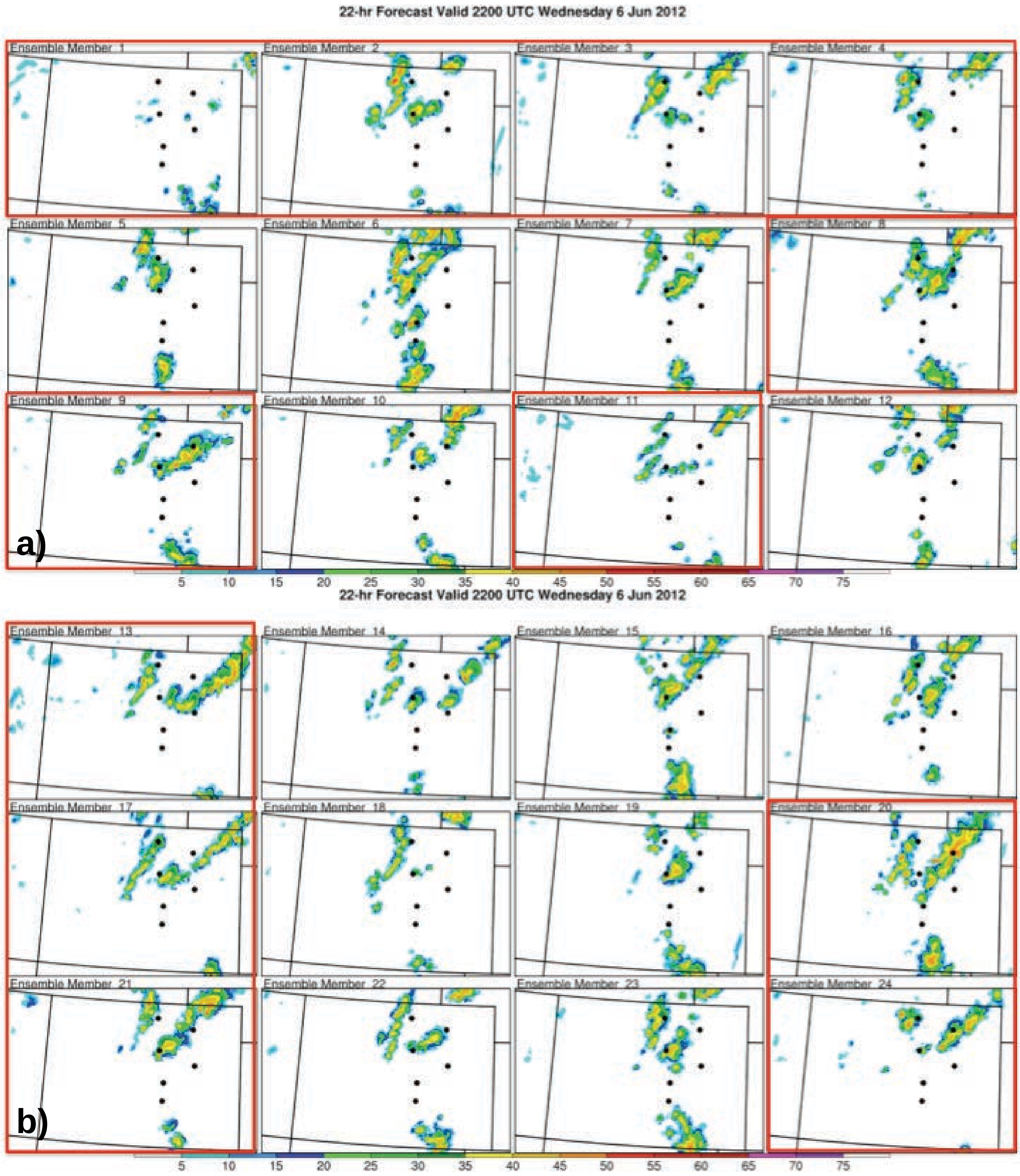


Fig. 3.5: KFTG radar reflectivity at approximately (a) 2200 UTC 6 June 2012 and (b) 2246 UTC 6 June 2012.



Fig, 3.6: Convection-allowing ensemble forecast of radar reflectivity valid at 2200 UTC 6 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.1 and Table 4.1). Red boxes outline same members as in Figure 3.4 for the purpose of comparing forecasted convective activity characteristics between 1800 UTC and 2200 UTC 6 June 2012.

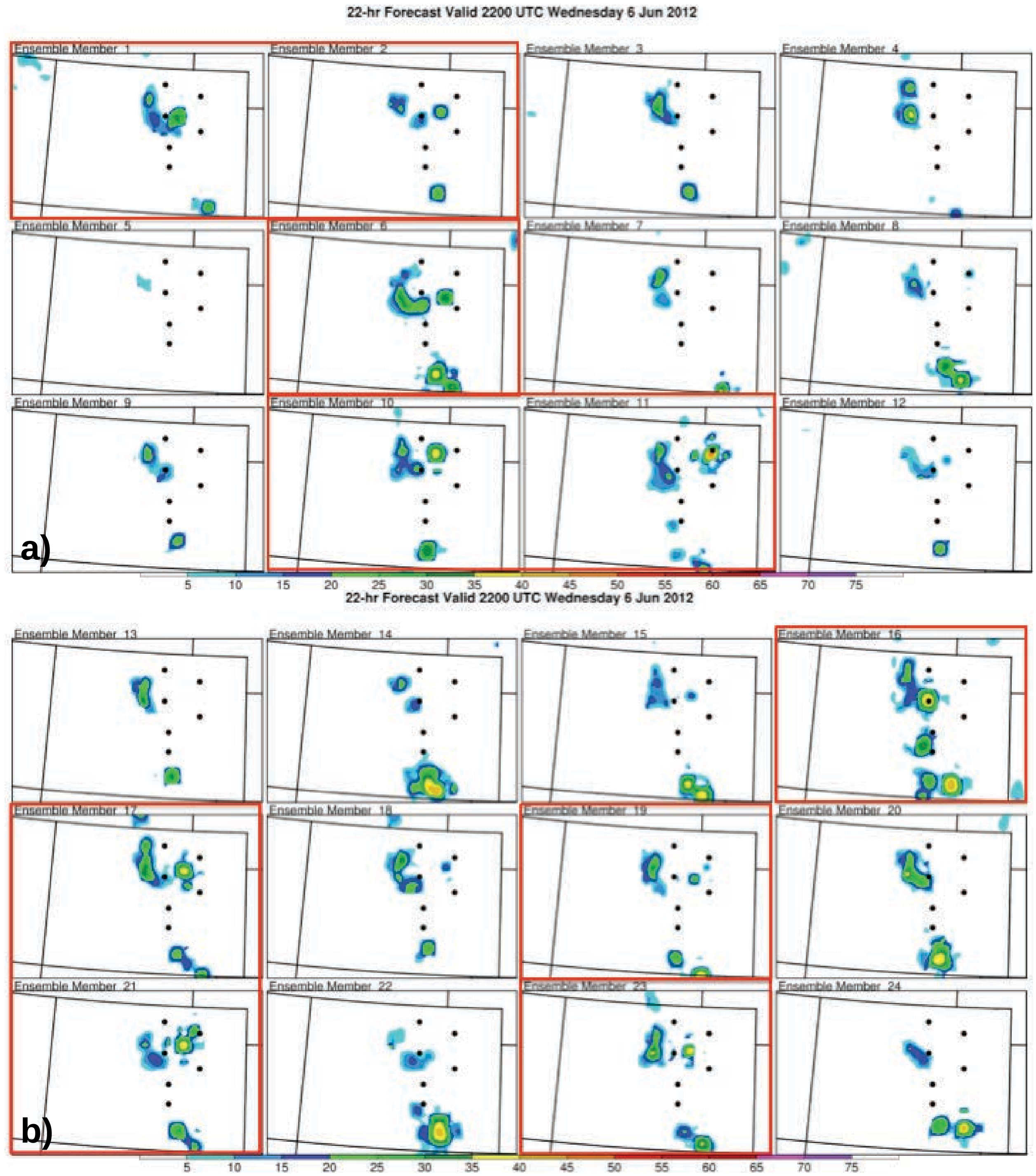


Fig. 3.7: Convection-parameterized ensemble forecast of radar reflectivity valid at 2200 UTC 6 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary geographic city locations for reference (see Fig. 4.3 and Table 4.1). Red boxes highlight those particular members that showed signs of convective activity over and to the lee of the foothills, as well as somewhere in the region traced by connecting the locations of Fort Collins, Denver, Limon and Fort Morgan.

As the evening progressed, the convection that had developed along the convergence boundary moved north and northeast, joining the storm cells in southeast Wyoming (Fig. 2.18). This union of storms created a broad area of precipitation that extended into northern Colorado. Additionally, two significant convective cells had developed near urbanized areas, one of which was southeast of Denver and the other was east of Colorado Springs. These two convective cells were isolated from the bulk of convective precipitation in northern Colorado and southeast Wyoming. As these explicit convective cells are small-scale and localized in nature, it is interesting to observe how both the convection-allowing and convection-parameterized ensembles handled the behavior of convection at this time. Some of the convection-allowing ensemble members were able to capture or at least suggest isolated convective cell features near Denver, Colorado Springs, or both at 0100 UTC 7 June or even an hour earlier (Fig. 3.8). In most cases, the convection-allowing ensemble members seemed to have quickly compiled the convection into a cluster of interacting thunderstorm cells - a feature associated with that of a mesoscale convective system, or an MCS. The convection-parameterized ensemble members faced much more difficulty in resolving the isolated convective cells near Denver and Colorado Springs; only a couple of members were able to give any indication of these features (Fig. 3.9). Broad areas of convection across northeastern Colorado were the primary features in these convection-parameterized ensemble forecasts, similar to the MCS signature in the convection-allowing ensemble forecasts but more smooth in nature. Although both ensembles misrepresented the widespread convection and precipitation further south than observed, it is apparent that the convection-allowing ensemble surpassed the convection-parameterized ensemble in adequately representing isolated convection.

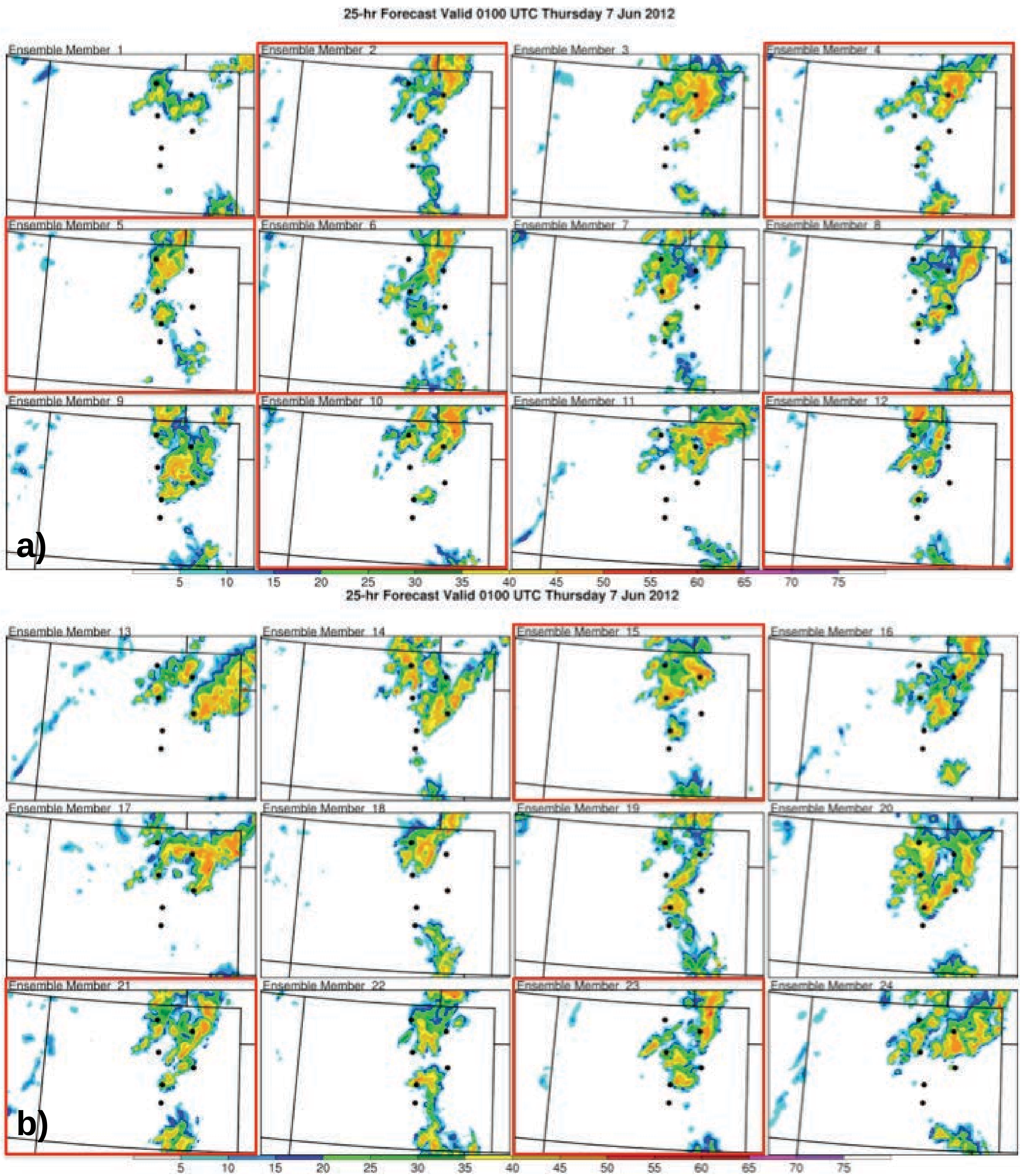


Fig. 3.8: Convection-allowing ensemble forecast of radar reflectivity valid at 0100 UTC 7 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.3 and Table 4.1). Red boxes highlight a sample of subjectively-chosen members that showed signs of isolate convective activity near the locations of Denver, Colorado Springs, or both.

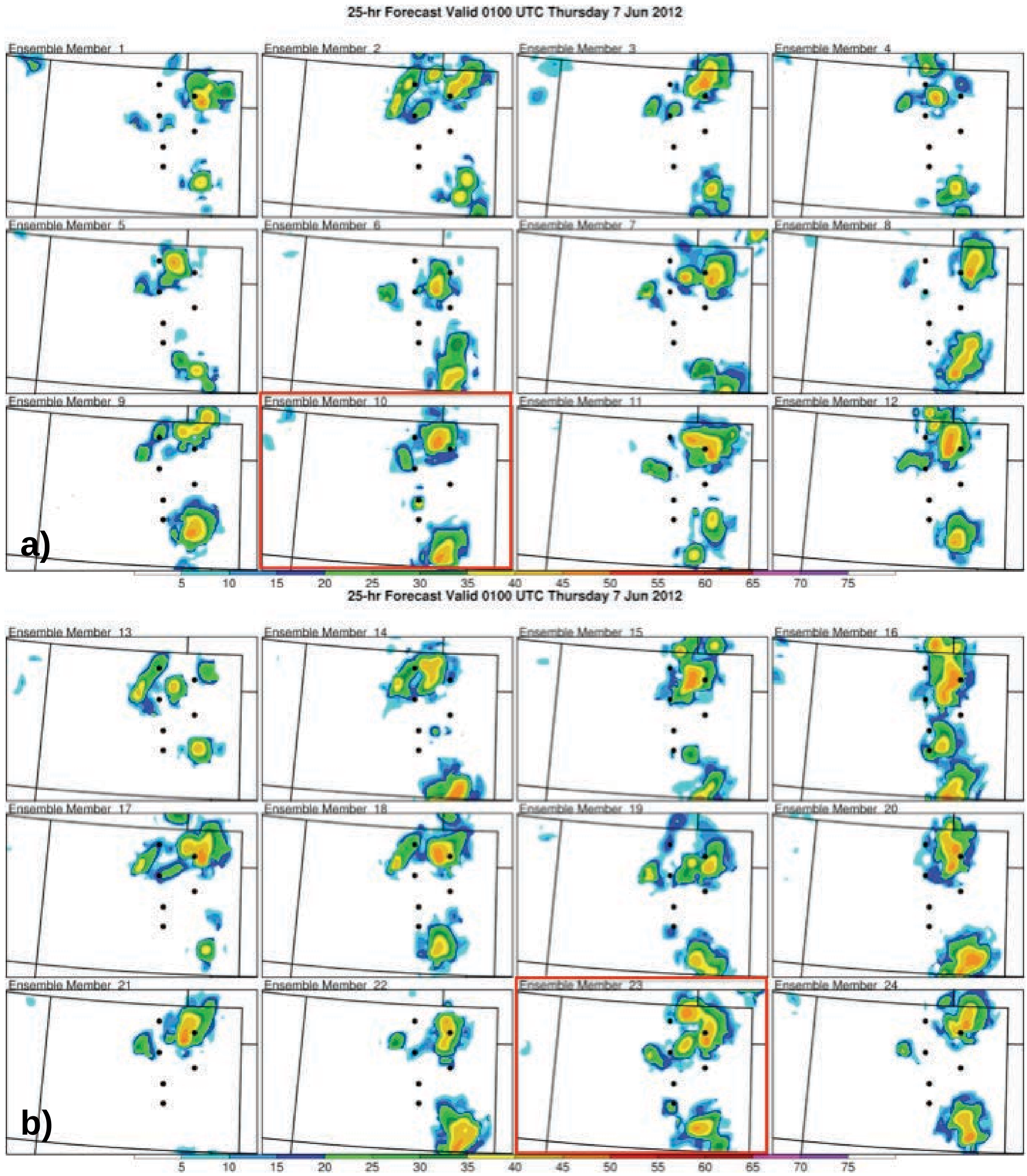


Fig. 3.9: Convection-parameterized ensemble forecast of radar reflectivity valid at 0100 UTC 7 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.3 and Table 4.1). Red boxes highlight a sample of subjectively-chosen members that showed signs of isolate convective activity near the locations of Denver, Colorado Springs, or both.

The primary convective cells near Denver and Colorado Springs had persisted throughout the night until about 0300 UTC 7 June, where the cell near Denver showed signs of slight dissipation and the cell near Colorado Springs began to move east and northeast (Fig. 2.18c, d). In addition, widespread precipitation expanded across the High Plains (Fig. 2.18d). This evolution of convection is perhaps a representation of the activity that was simulated earlier by both ensembles. Meanwhile, new convection began to initiate off of the northern foothills, expanding and increasing in intensity as it moved northeast into southeast Wyoming (Fig. 3.10). A majority of the convection-allowing and convection-parameterized ensemble members missed this development, as the MCS was the chief forecast feature across the High Plains (not shown).

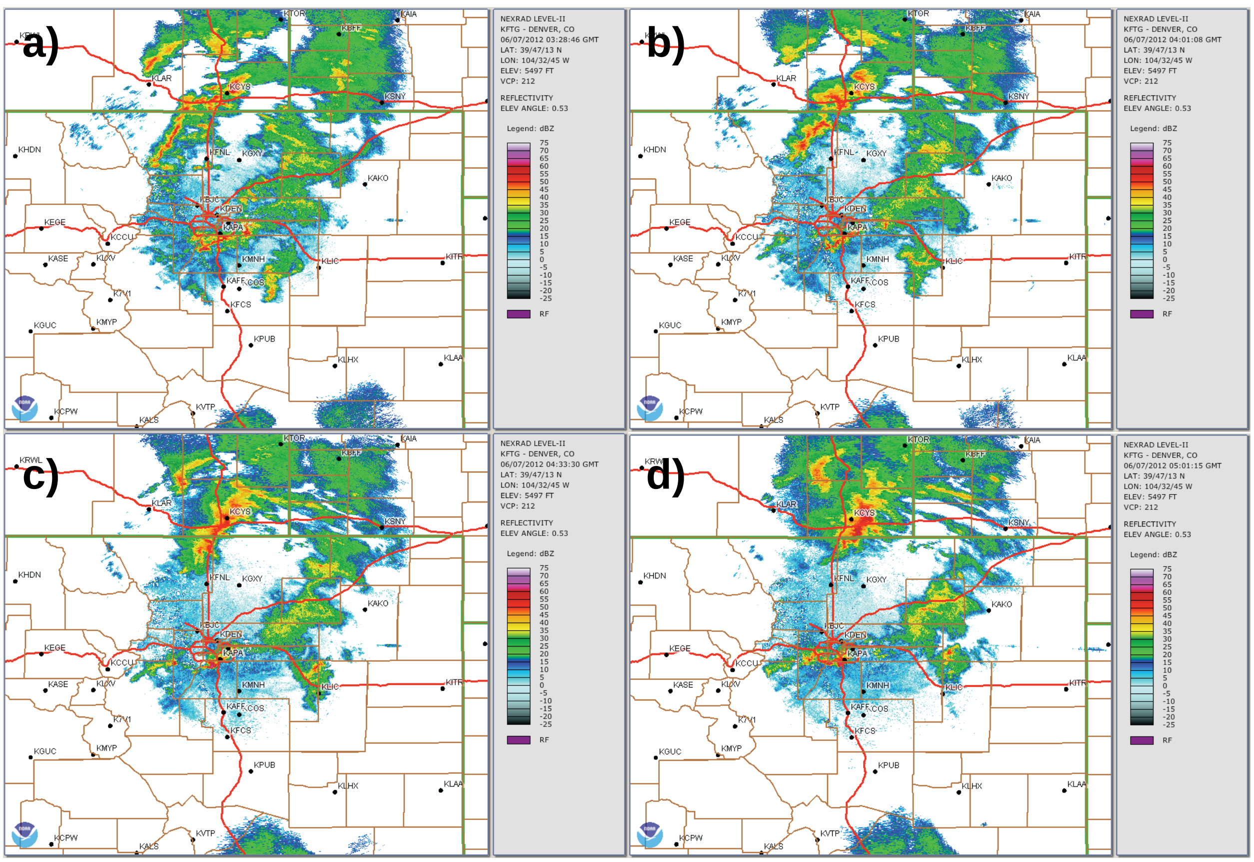


Fig. 3.10: KFTG radar reflectivity at approximately (a) 0329 UTC 7 June 2012, (b) 0401 UTC 7 June 2012, (c) 0433 UTC 7 June 2012, and (d) 0501 UTC 7 June 2012.

Interestingly, the convection south and east of Denver continued to persist despite its decrease in intensity (Figs. 2.18 and 3.10). Eventually, this area of convection was joined by other convection that had developed off the central foothills and was moving east (Fig. 3.10c, d). In other areas, widespread precipitation covered southeast Wyoming and parts of northern Colorado (Fig. 3.10d). The enhanced convection near Denver then slowly moved northeast as it expanded and decreased in intensity (Fig. 3.11). The MCS forecasted by most of the convection-allowing and convection-parameterized ensemble members had advanced east and northeastward, such that by 0900 UTC 7 June, any sign of leftover convection was confined to northeast Colorado and into the Nebraska panhandle (Figs. 3.12 and 3.13). Furthermore, both ensembles were unsuccessful at specifically capturing the last-minute enhanced convective activity near Denver, but were able to show some signs of the leftover activity in northeast Colorado that was observed.

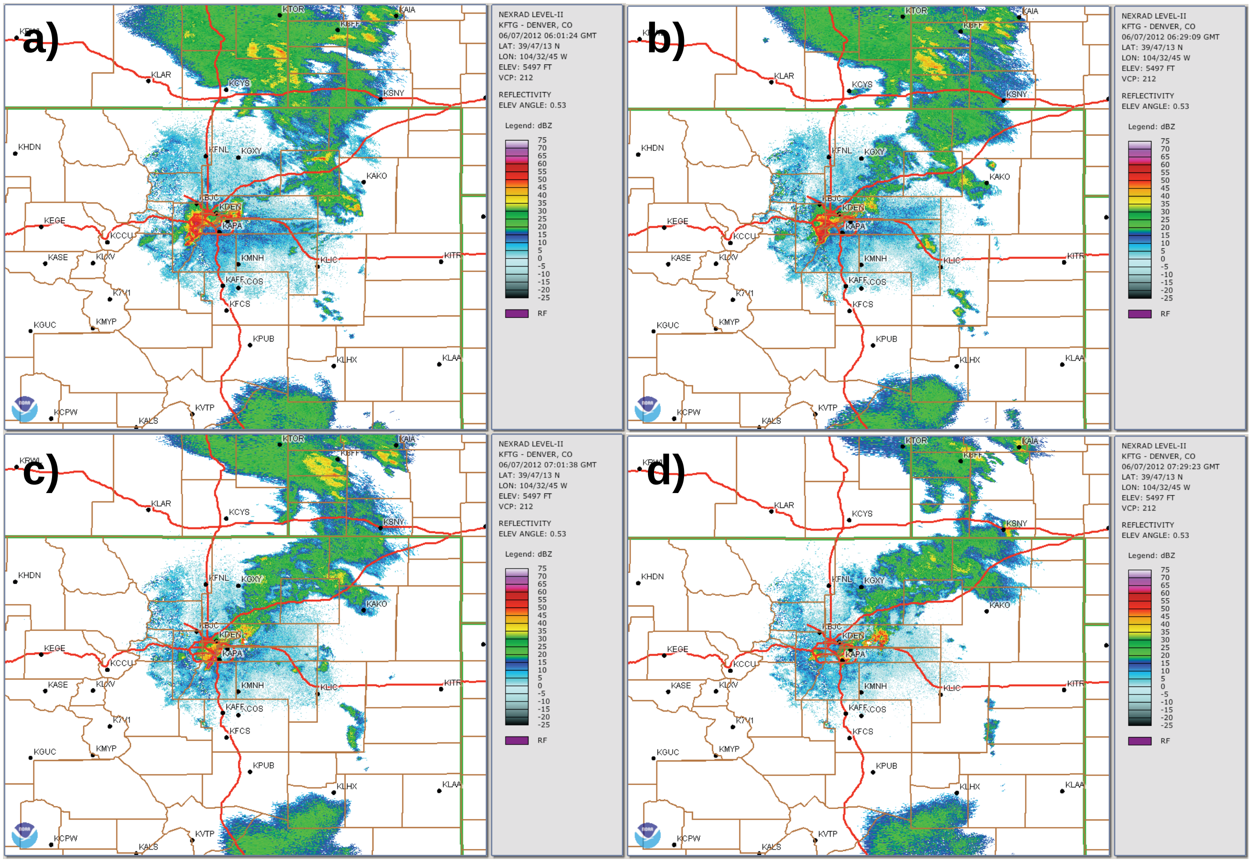


Fig. 3.11: KFTG radar reflectivity at approximately (a) 0601 UTC 7 June 2012, (b) 0629 UTC 7 June 2012, (c) 0702 UTC 7 June 2012, and (d) 0729 UTC 7 June 2012.

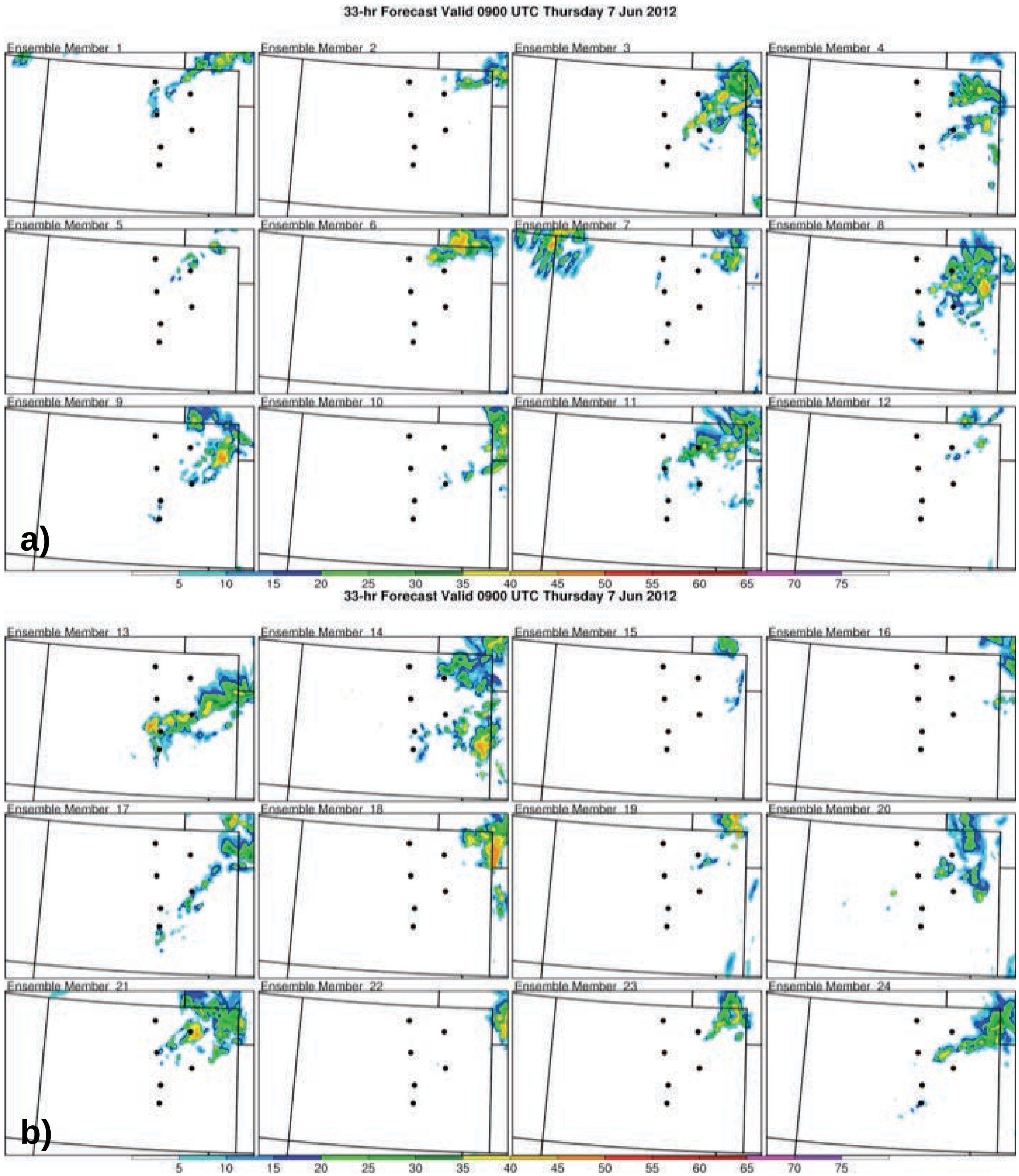


Fig. 3.12: Convection-allowing ensemble forecast of radar reflectivity valid at 0900 UTC 7 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.3 and Table 4.1).

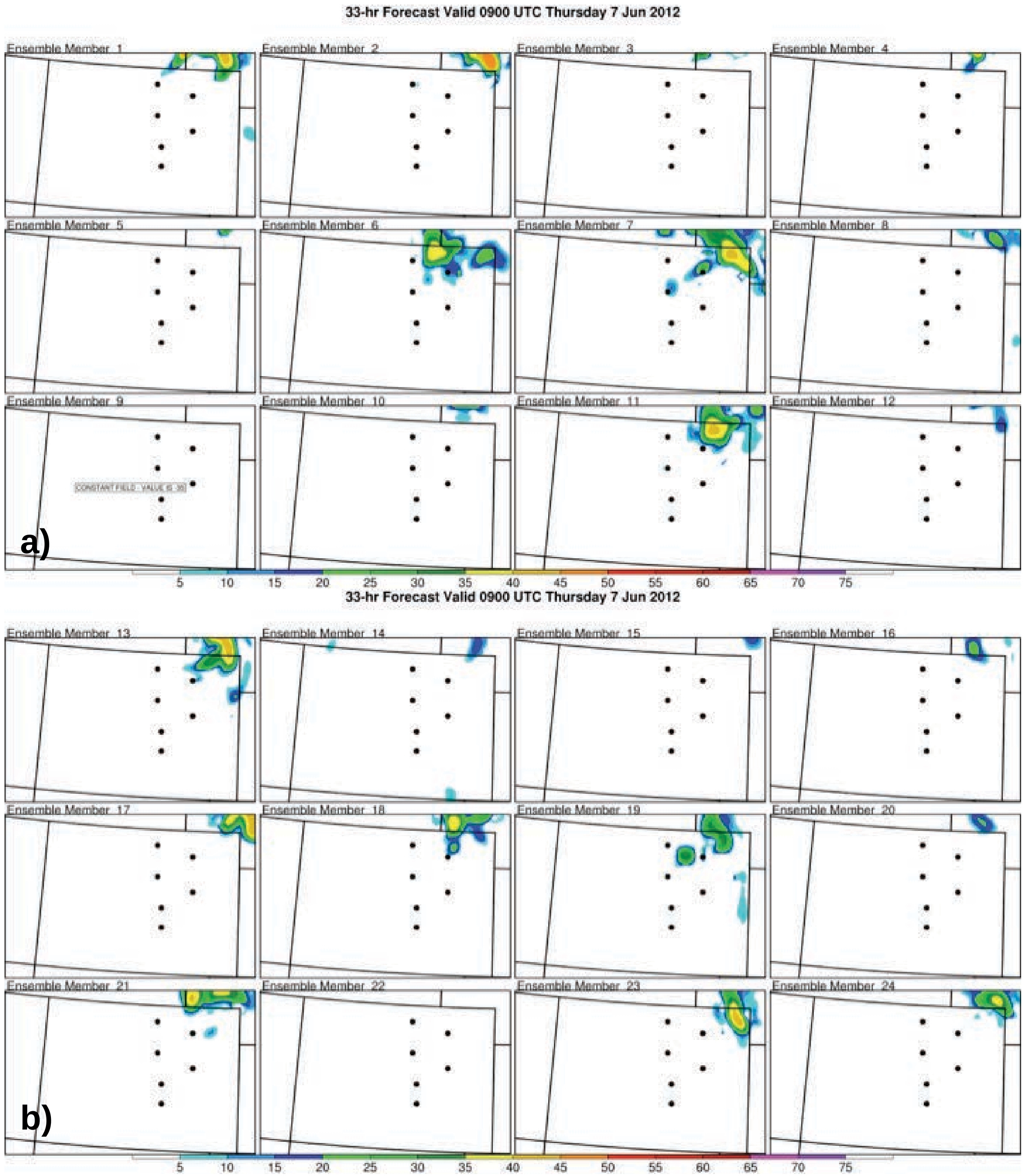


Fig. 3.13: Convection-parameterized ensemble forecast of radar reflectivity valid at 0900 UTC 7 June 2012 for (a) ensemble members 1 through 12 and (b) ensemble members 13 through 24. Black dots symbolize primary reference locations (see Fig. 4.3 and Table 4.1).

Although the convection-allowing ensemble forecasts provided a better overview of the mesoscale convective activity, a more comprehensive analysis is warranted to investigate those particular forecast characteristics aforementioned. How well did the convection-allowing ensemble members capture the mesoscale features responsible for convective initiation along and near the Front Range? How well were the mesoscale processes represented that characterized the distinct behavior of the isolated convective cells observed? These are the questions that are addressed and discussed further in section 3.3.

3.2.1b Forecasting precipitation

As previously discussed in the case study, the 24-hour Stage IV precipitation accumulation analysis valid at 1200 UTC 7 June showed a widespread swath of precipitation from central Colorado north into southeast Wyoming and the Nebraska panhandle (Fig. 2.16). Heavier amounts of precipitation fell near the cities of Cheyenne, Denver and Colorado Springs. Taken as a whole, the 24-hour precipitation accumulation forecasts from the convection-allowing ensemble were able to sufficiently identify the approximate geographic area of where to expect precipitation (Figs. 2.16, 3.14, and 3.15). They also provided a general sense of the likely range in precipitation amounts, and where to possibly expect the greatest precipitation. These general observations corresponded well to those found by Clark et al. (2009) in that simulations using convection-allowing resolution (4 km) represented the spatial characteristics of convective precipitation better than a coarser model using convective parameterizations. However, the forecasts herein illustrated several differences in the spatial and quantitative characteristics of precipitation, some of which are correlated to how the ensemble members forecasted the radar reflectivity. For example, the majority of the 24-hour precipitation forecasts show an eastward displacement of where most of the precipitation would fall compared to observations. This is consistent with the eastward displacement of convective initiation (Fig. 3.6), and was added to by the simulated MCS activity that impacted northeast Colorado (Fig. 3.8). Furthermore, there seems to have been an overestimation of precipitation across the High Plains embedded within a broader swath of precipitation than what was observed. As far as capturing the precipitation maxima near the urbanized areas, many of the ensemble members displaced, missed, or underestimated the precipitation compared to what had actually fallen.

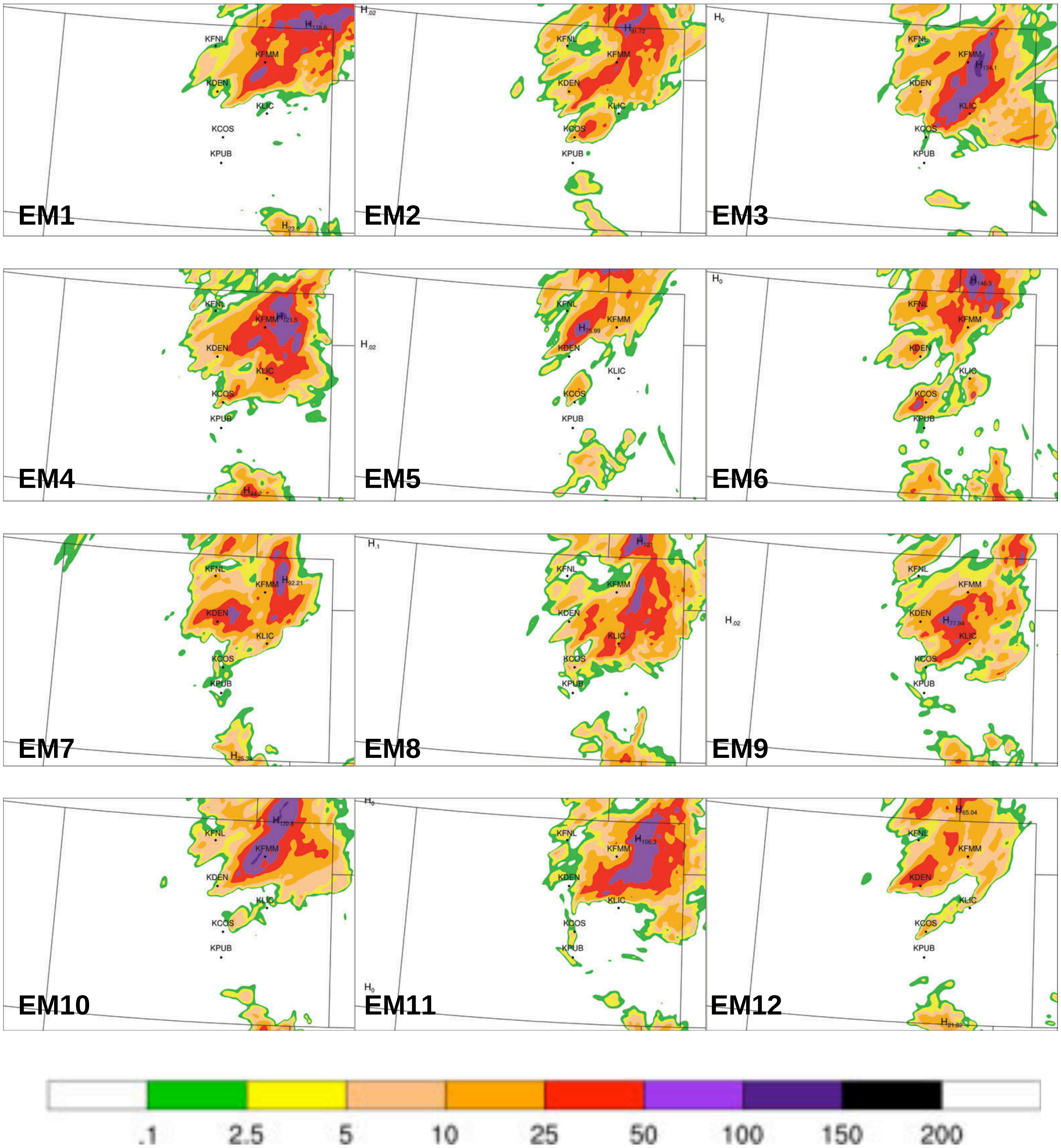


Fig. 3.14: Convection-allowing ensemble forecasts of 24-hour accumulated precipitation (mm) valid at 1200 UTC 7 June 2012 for ensemble members (EMs) 1 through 12.

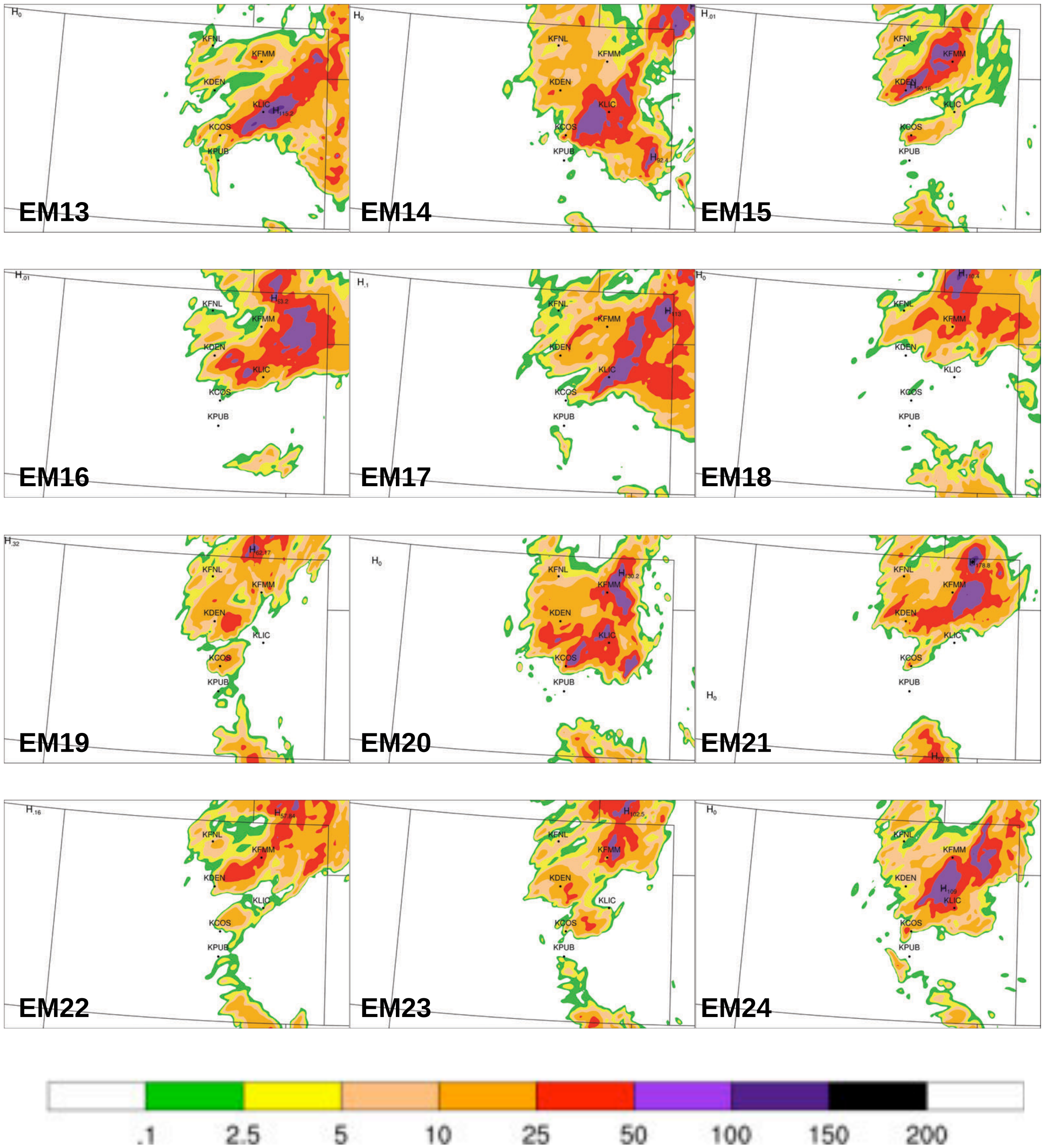


Fig. 3.15: Convection-allowing ensemble forecasts of 24-hour accumulated precipitation (mm) valid at 1200 UTC 7 June 2012 for ensemble members (EMs) 13 through 24.

Given the quantitative characteristics illustrated by the convection-allowing ensemble members, it was of interest to investigate how the ensemble predicted the probability of exceeding precipitation at various thresholds. This was calculated over the 6-hour time period of greatest activity, namely 0000 UTC 7 June through 0600 UTC 7 June. The convection-allowing ensemble showed a 10% to 30% probability of exceeding 1 inch of precipitation across northeastern Colorado, with probabilities of 30 to 50% embedded within this region (Fig. 3.16a). As the threshold increased, the probability of exceedence decreased such that there was no probability of surpassing 3 inches of precipitation (Fig. 3.16a-c). What is interesting to note is the pattern illustrated by the probability of exceeding 1 inch of precipitation; notice how the pattern resembles many of the convection-allowing 24-hour accumulated precipitation forecasts (Figs. 3.16a, 3.14, and 3.15). As a result, the same probabilities were calculated for the convection-parameterized ensemble to determine if a similar observation would follow.

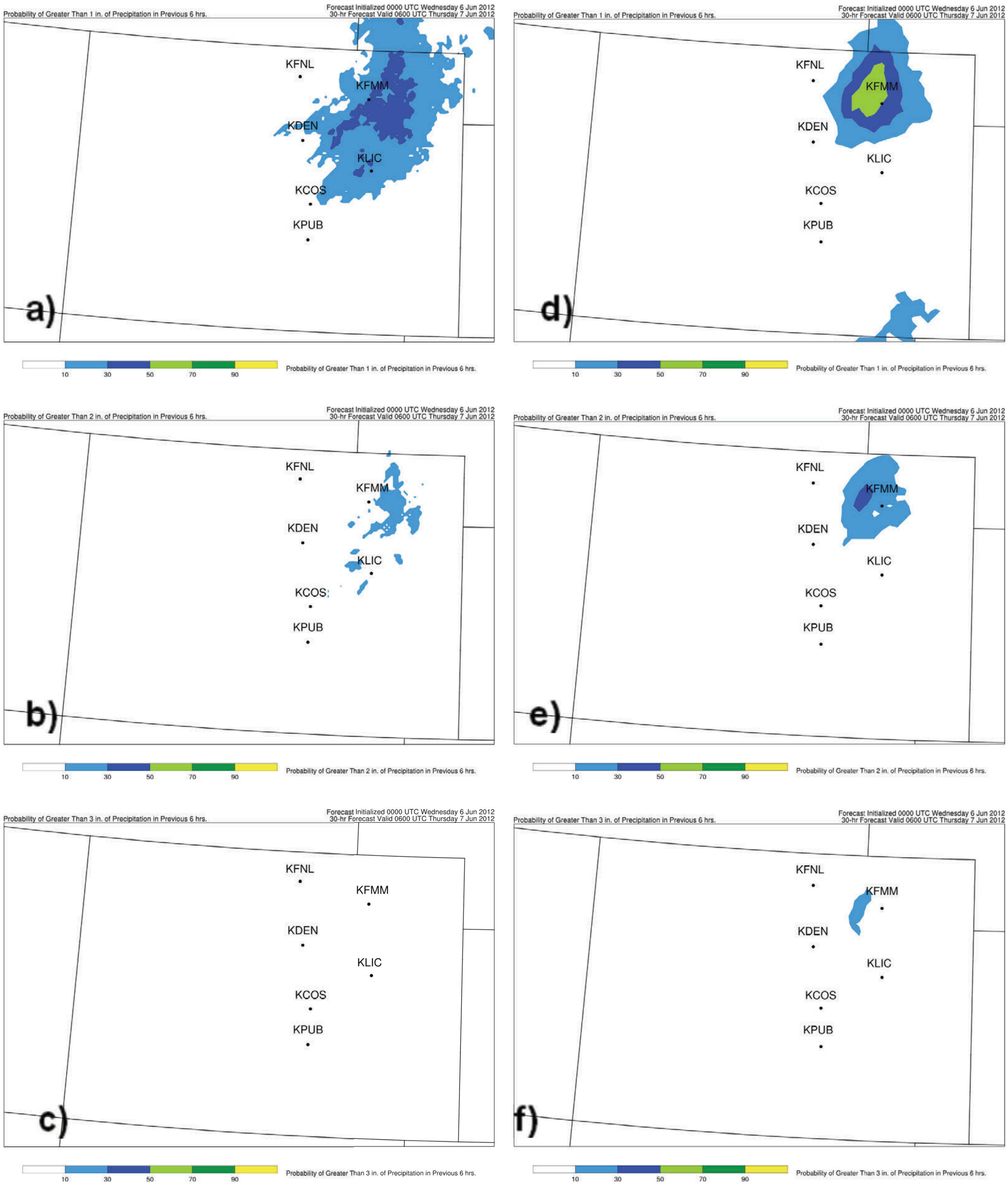


Fig. 3.16: Comparison between the convection-allowing [(a)-(c)] and convection-parameterized [(d)-(f)] ensemble forecasts for the probability of exceeding the following precipitation amounts - (a), (d) 1 inch; (b), (e) 2 inches; (c), (f) 3 inches.

The convection-parameterized ensemble showed a 10% to 30% probability of exceeding 1 inch of precipitation in northeastern Colorado, with probabilities of up to 70% embedded within this area (Fig. 3.16d). It is apparent that these probabilities paint a circular pattern, particularly with the highest probabilities being just west of Fort Morgan. Similar to the convection-allowing ensemble, an increase in the threshold led to a decrease in the probabilities (Fig. 3.16d-f), with little to no probability for exceeding 3 inches of precipitation. This "bullseye" of probability for exceeding 1 inch of precipitation near Fort Morgan resembles the 24-hour accumulated precipitation forecasts generated by the convection-parameterized ensemble (Figs. 3.16d, 3.17, and 3.18). In this case, a majority of the members forecasted precipitation exceeding 50 mm (2 inches) in northeastern Colorado, especially near Fort Morgan (Figs. 3.17 and 3.18). Compared to the 24-hour accumulated precipitation analysis, areas near Fort Morgan received an estimated 1 inch to 2 inches of precipitation, with higher amounts further west (Fig. 2.16). Therefore, the conservative nature of the convection-allowing ensemble probabilities of exceeding 2 inches of precipitation within this area was a better forecast compared to that of the convection-parameterized ensemble probabilities. It is believed that the convection-parameterized ensemble had insufficient spread in its convective processes and, subsequently, its precipitation distribution. Since the convection-parameterized ensemble probabilities of exceedence and accumulated precipitation forecasts were not a reasonable representation of what was observed, the forecasts from the convection-allowing ensemble served as the chief modeling results from which our in-depth mesoscale analysis was executed.

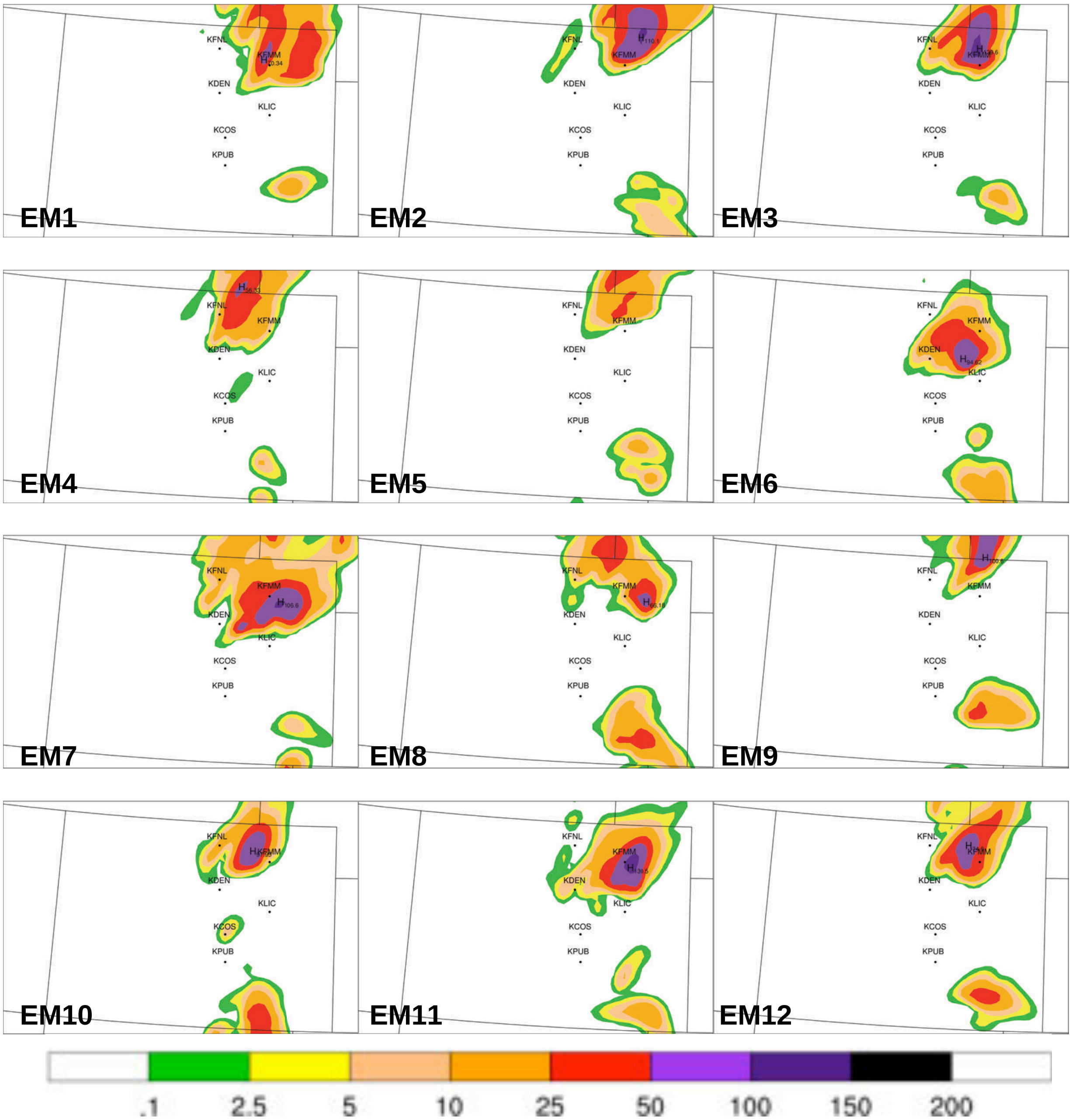


Fig. 3.17: Convection-parameterized ensemble forecasts of 24-hour accumulated precipitation (mm) valid at 1200 UTC 7 June 2012 for ensemble members (EMs) 1 through 12.

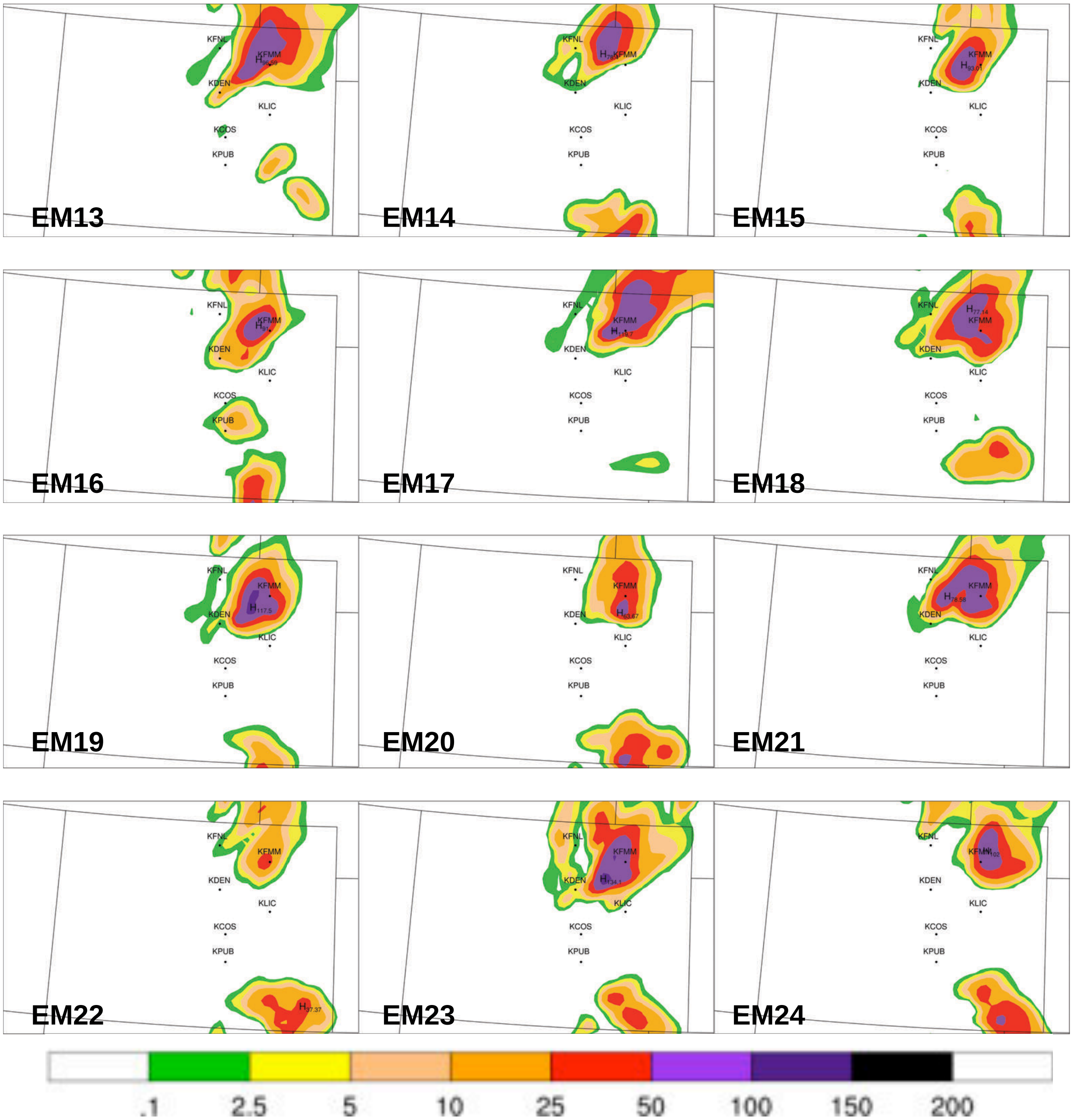


Fig. 3.18: Convection-parameterized ensemble forecasts of 24-hour accumulated precipitation (mm) valid at 1200 UTC 7 June 2012 for ensemble members (EMs) 13 through 24.

3.2.1c Fractions Skill Score

The underlying forecast uncertainties in the convection-allowing ensemble members regarding precipitation accumulation characteristics motivated further study into how well the members were able to capture the principle mechanism responsible for the convection on 6 June.

It is believed that depending on how well the ensemble members resolved the development of the convergence boundary would influence the behavior of forecasted convection and ultimately the precipitation forecasts. The 24-hour precipitation accumulation forecasts were considered in a subjective manner to identify those ensemble members that adequately forecasted the geographic location, spread, and amount of precipitation compared to observations. The resulting members that were subjectively thought to have done well were #2, #15, #19, #20, and #24. Given that there were quite a few members that satisfied these criteria, a subsequent objective approach was implemented to help dilute the selections. The Fractions Skill Score was calculated for each ensemble member in forecasting precipitation between 1200 UTC 6 June and 1200 UTC 7 June, or between forecast hours 12 and 36. As will be shown, this objective method identified members that did not match all that were subjectively chosen. Only two members, #2 and #5, were described as "good" members subjectively and objectively.

The Fractions Skill Score analysis shows decent spread in skill for ensemble members forecasting precipitation at the lower thresholds, namely between 12.5 mm and 50 mm (Fig. 3.19). At thresholds greater than 50 mm, there is much less spread in the skill of the ensemble members relative to the lower thresholds. It is apparent that ensemble member #5 performed exceptionally well relative to all the other members, at least for thresholds greater than 12.5 mm and less than 75 mm. There was also a smaller group of other ensemble members that had more skill at the 12.5 mm threshold than ensemble member #5, but experienced a reduction in skill at greater thresholds. This smaller group comprised of ensemble members #2, #6, and #12. Interestingly, while ensemble member #2 had the greatest skill score above all at a threshold of 12.5 mm, its skill decreased at greater thresholds and was overcome by other ensemble members that had slightly lower skill scores than #2 at the lowest threshold. These ensemble members include #5, #6, #12, and #15.

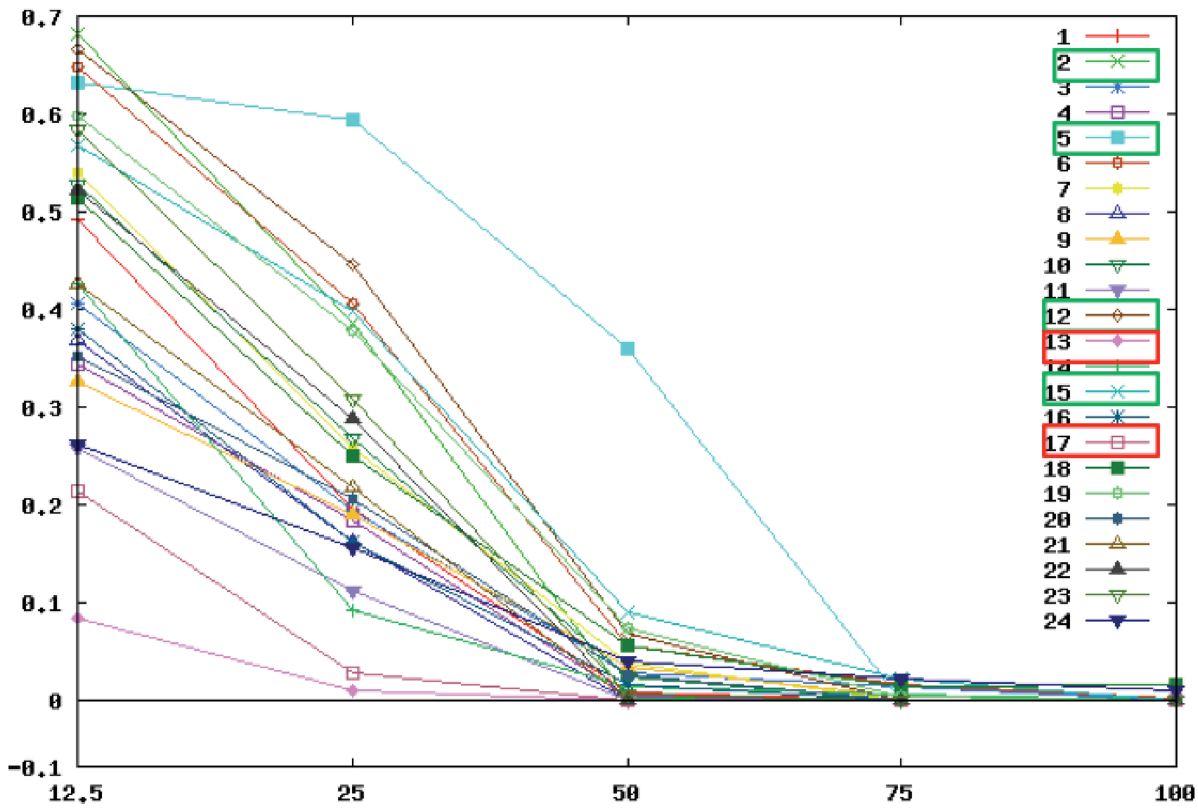


Fig. 3.19: The Forecast Skill Score (FSS) of all convection-allowing members in forecasting various thresholds of precipitation during forecast hours 12 and 36 (i.e. 1200 UTC 6 June 2012 through 1200 UTC 7 June 2012). Varying precipitation thresholds (mm) are on the x-axis. FSS score is on the y-axis. Green (red) boxes denote the "good" ("poor") ensemble members.

Other noticeable observations are the two ensemble members that had the worst skill in forecasting the 24-hour period of precipitation, ensemble member #13 and #17. The rest of the ensemble members possessed mediocre skill, ranging from 0.26-0.6 at a threshold of 12.5 mm and decreasing in skill as the threshold value increased. Overall, ensemble members #2, #5, #12, and #15 represented the "good" members in the sense that their forecast skill score were among the highest of all members throughout the varying thresholds. Given the resemblance of ensemble member #6 to member #12, and that member #12 had greater skill throughout, member

#6 was not considered for further study. In addition, ensemble members #13 and #17 represented the “poor” members as they received the lowest skill scores among all members. The selected groups of ensemble members illustrating the two extreme cases of precipitation forecasting ability motivated further examination of what could be causing the difference.

3.3 Comparison of “good” and “bad” convection-allowing ensemble members

3.3.1 Convergence boundary forecasts

As previously discussed, a convergence boundary began to develop during the afternoon hours on 6 June (Fig. 2.6b). The boundary extended from the southwest corner of Morgan County, southwest towards the southeast corner of Douglas County in Colorado. Modeled streamline analysis and radar reflectivity was generated to assess the ability of the convection-allowing ensemble in predicting the observed convergence boundary to the east and southeast of Denver. While the “good” ensemble members were able to roughly capture the convergence boundary and place it in the more or less geographic area (Fig. 3.20a-d), the “poor” ensemble members were unable to do so. Although ensemble members #13 and #17 were able to capture the convergence boundary (even more so than the “good” ensemble members), the placement of that boundary was well displaced to the south and east compared to what was observed (Fig. 3.20e, f). Another apparent mesoscale feature that differentiated between the “good” and “poor” ensembles is the Denver Cyclone. The “good” ensemble members were able to resolve a cyclonic circulation roughly in the same vicinity in which it was observed, although may have had it slightly displaced to the north and east (Figs. 3.20a-d and 2.7b). The “poor” ensemble members, however, showed no indication of any such circulation near Denver.

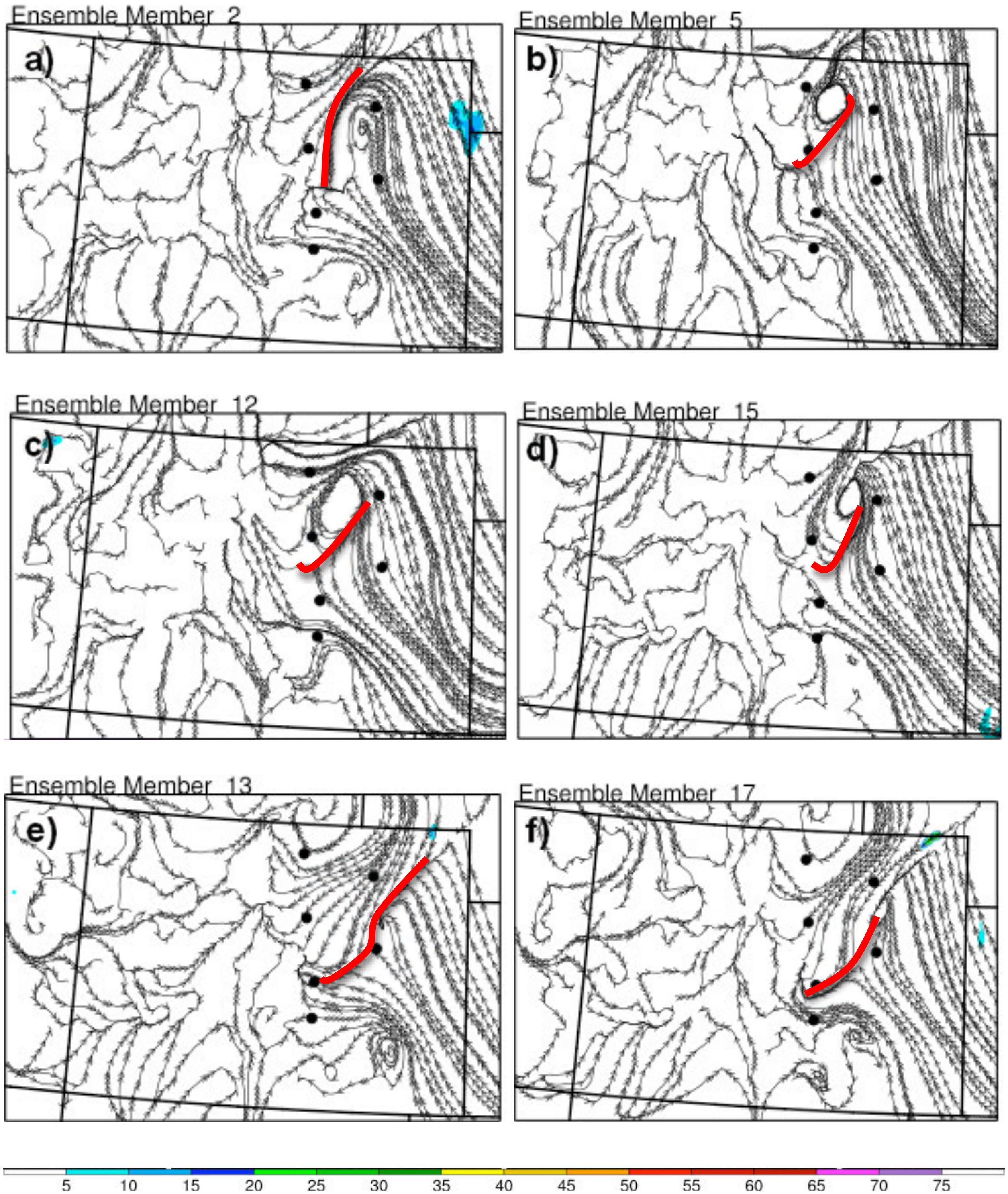


Fig. 3.20: Modeled streamline and radar reflectivity analysis of the "good" members [(a) – (d)], and "poor" members [(e) and (f)] valid at 1700 UTC 6 June 2012. Red line subjectively denotes the convergence boundary.

Observed convection began to initiate at approximately 2100 UTC 6 June along the convergence boundary and in southeast Wyoming (Fig. 2.8b). Although half of the ensemble members predicted convective initiation earlier than observed, this convective initiation was primarily in extreme northeast Colorado and into the Nebraska panhandle (Fig. 3.4). The “good” ensemble members were able to capture convective development in the vicinity of where the predicted convergence boundary was placed, and near the time of observed boundary-associated convection (Figs. 3.4 and 3.21a-d). Such convection continued to build south and west along the boundary, while convection later began to develop off of the foothills. This convection then moved north and east, eventually merging with the predicted boundary-associated convection and producing outflow at its leading edge as indicated by the streamlines. For the "poor" ensemble members, convection initiated on the northern fringe of the easterly-displaced convergence boundary, and continued to build south and west along that boundary (Fig. 3.21e, f). Similar to the “good” ensemble members, the boundary convection was joined by the convection off the foothills and congealed into a cluster of thunderstorms as it moved north and east.

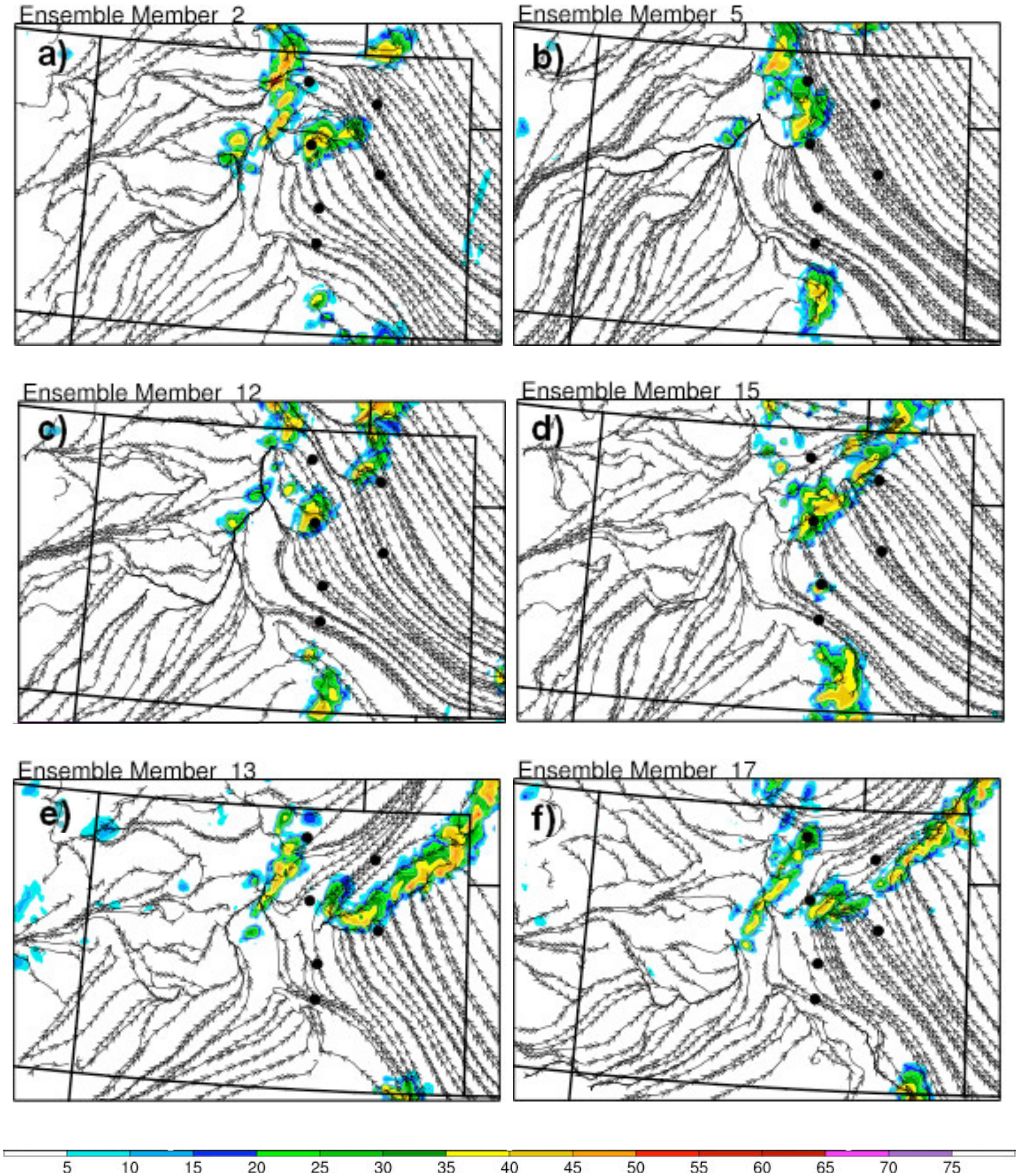


Fig. 3.21: Modeled streamline and radar reflectivity analysis of the "good" members [(a) – (d)], and "poor" members [(e) and (f)] valid at 2200 UTC 6 June 2012.

The differences in how the “good” and “poor” ensemble members captured the presence and geographic location of the convergence boundary inspired great inquiry into whether the predicted boundary was indeed its own feature, or was it a manifestation of the cold front discussed in the case study. In the attempt to answer this question, the forecasted surface temperature for all the “good” and “poor” ensemble members was examined during the time period of the observed developing convergence boundary (1800 UTC 6 June). Amazingly, the “good” ensemble members altogether illustrated the cold front bounded to the border of Wyoming, Nebraska, and Colorado as indicated by the temperature gradient (albeit it is not a strong one; Fig. 3.22a-d). On the contrary, the “poor” ensemble members depicted the cold front across northeastern Colorado, extending from the Nebraska panhandle southwestward to Colorado Springs (Fig. 3.22e, f). These observations suggests that the “good” ensemble members were able to focus convective initiation along the predicted convergence boundary, as observed, whereas the “poor” ensemble members may have focused convective initiation along a boundary that is associated with a cold frontal passage. Given the performance of the “poor” ensemble members, it is possible that these members either simulated a cold front that extended too far south, or perhaps simulated too strong of a cold front that managed to “wash out” the convergence boundary. Another option to consider would be that the “poor” members simulated a front that passed through much too quickly.

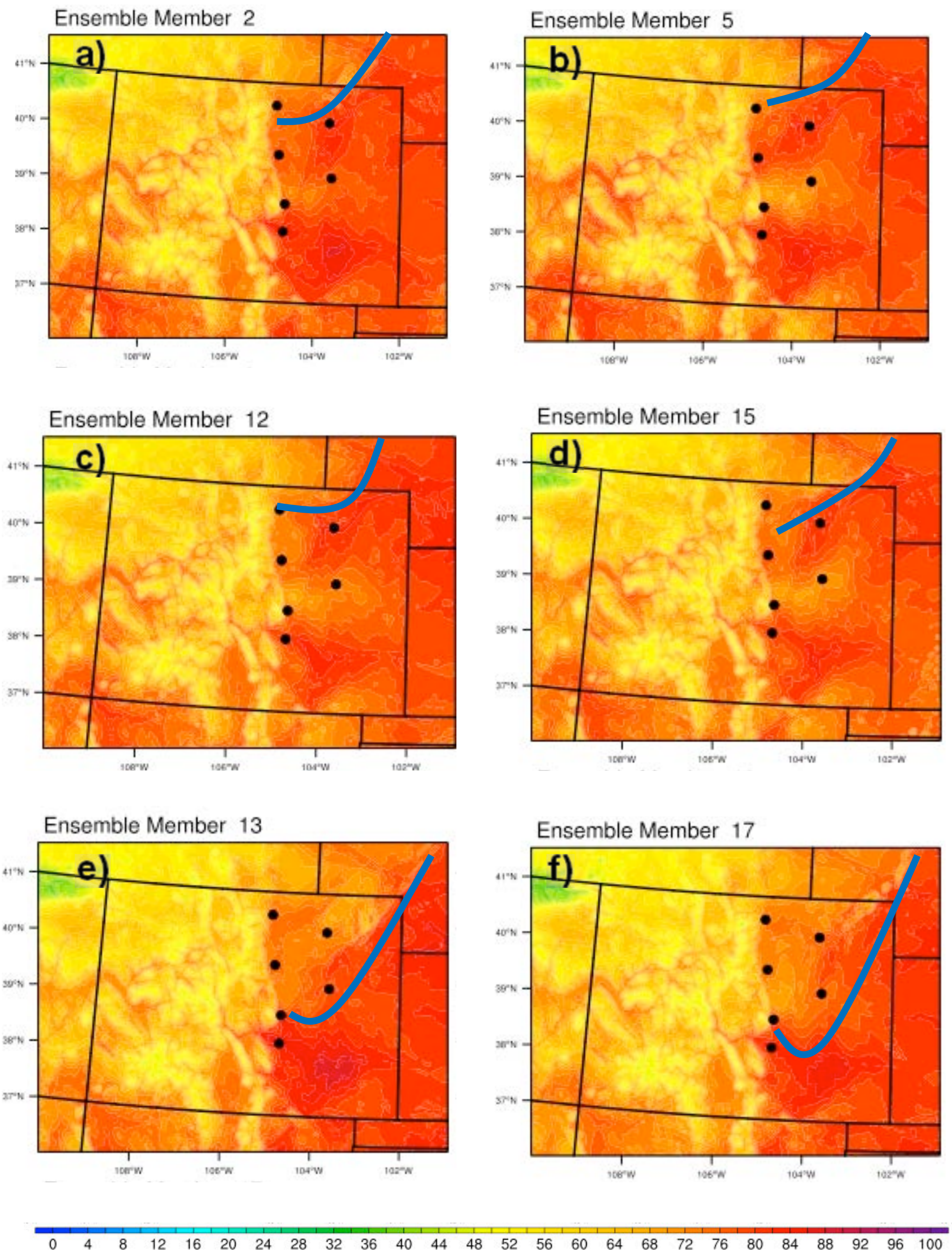


Fig. 3.22: Modeled surface temperature analysis of the "good" members [(a) – (d)], and "poor" members [(e) and (f)] valid at 1800 UTC 6 June 2012. Blue line subjectively denotes cold front.

3.3.2 Precipitation forecasts

Comparing the 24-hour accumulated precipitation forecasts between the “good” and “poor” ensemble members not only illustrated key differences in the spatial characteristics of precipitation, but also reflected how the resolved convergence boundary focuses where the precipitation was predicted to fall. Regarding the “good” ensemble members, it is apparent that overall much of the forecasted heavy precipitation had fallen in an area parallel to where that particular member had predicted the convergence boundary (Figs. 3.23a-d and 3.20a-d). Additionally, the forecasted precipitation was expressed in a “swath” pattern, generally extending from Denver northeast towards the Wyoming/Nebraska border. These ensemble members also underestimated but at least attempted to predict the local urban areas that had received the heaviest precipitation amounts (Fig. 3.23), and forecasted these precipitation maxima better than the “poor” ensemble members. The “poor” ensemble members predicted much of the heavy precipitation to fall in the region similar to where they had resolved the convergence boundary (i.e. the cold front; Figs. 3.24a, b and 3.20e, f). As a consequence, the forecasted precipitation was displaced further south and east than observed (Fig. 3.24). These ensemble members also did not perform as well in predicting the local precipitation maxima near the metropolitan areas.

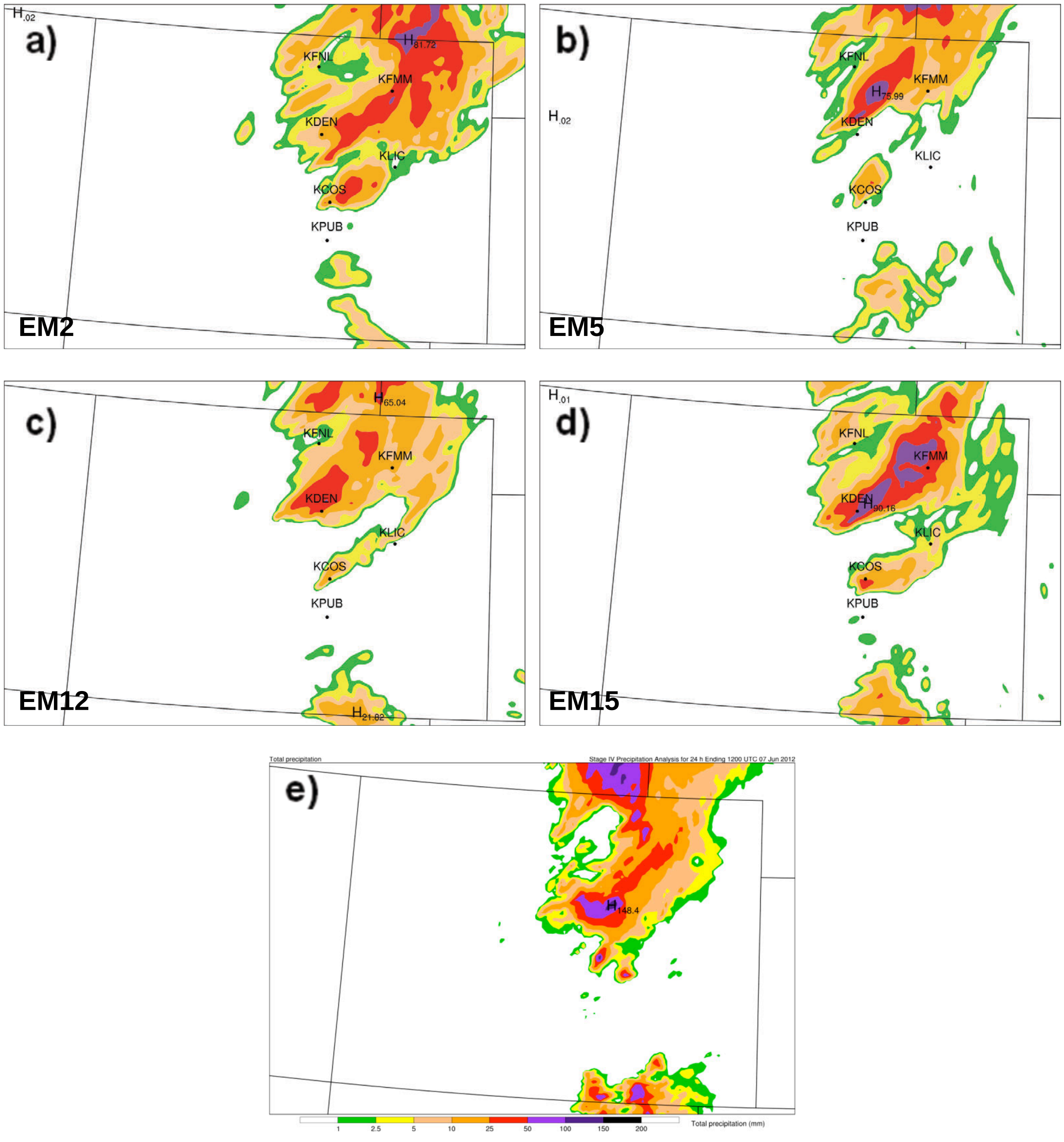


Fig. 3.23: Comparison between the 24-hour accumulated precipitation (mm) forecasts of the "good" members [(a) – (d)], and (e) Stage IV 24-hour precipitation analysis, both valid on 1200 UTC 7 June 2012.

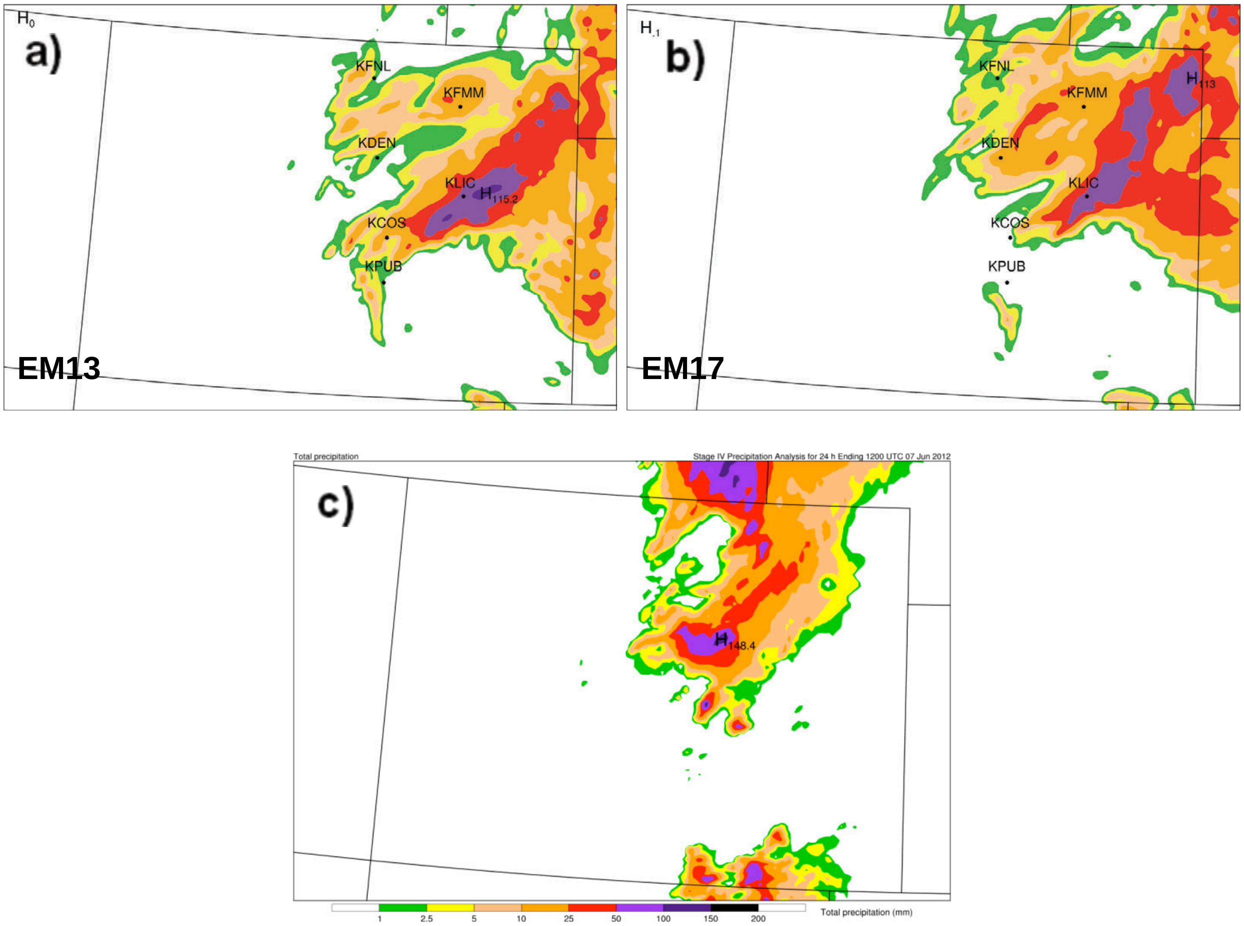


Fig. 3.24: Comparison between the 24-hour accumulated precipitation (mm) forecasts of the "poor" members [(a), (b)], and (e) Stage IV 24-hour precipitation analysis, both valid on 1200 UTC 7 June 2012.

The 6-hour accumulated precipitation forecasts valid at the three time periods of greatest activity (0000 UTC, 0600 UTC, and 1200 UTC 7 June 2012) associated with the "good" ensemble members showed a reasonable representation on the progression of accumulated precipitation (Figs. 3.25, 3.26, and 3.27). It seems as though these members overestimated and underestimated the precipitation accumulations for the first and third active period, respectively. As for the second and most active period, these members performed well in forecasting the heavier amounts of precipitation within the vicinity of where it was observed. It is impressive how these members as a whole suggested the main areas that could expect heavy precipitation during the most active period, especially for the city of Denver and Colorado Springs. Compared to the “poor” ensemble members, the overestimation, spatial extent, and displacement of precipitation were the main errors during all three periods of activity (Figs. 3.28, 3.29, and 3.30). This may be attributed to how the members were unable to resolve and distinguish between two meteorological features, those being the cold front and the convergence boundary.

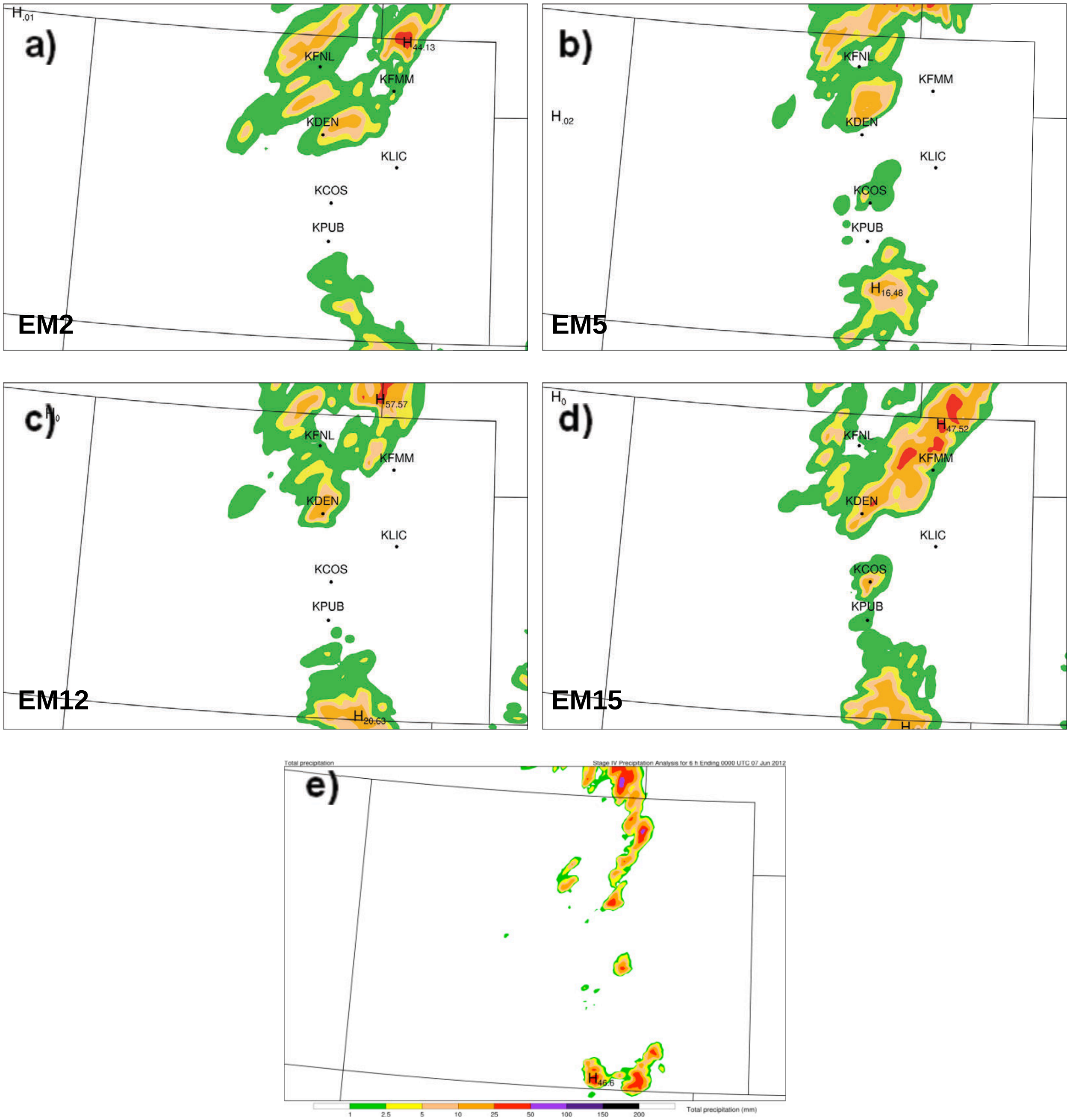


Fig. 3.25: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the "good" members [(a) - (d)], and (e) Stage IV 6-hour precipitation analysis, both valid on 0000 UTC 7 June 2012.

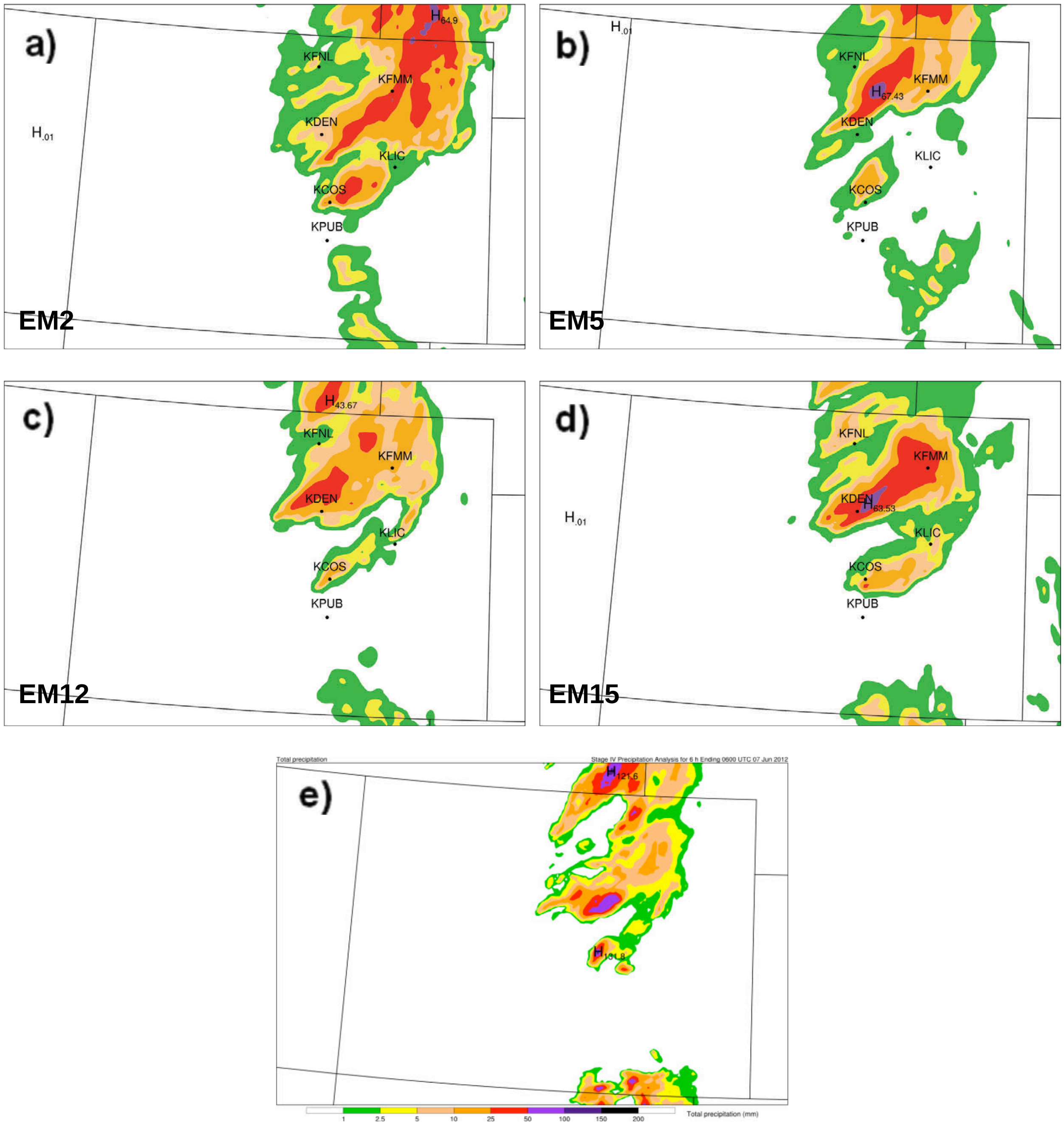


Fig. 3.26: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the “good” members [(a) - (d)], and (e) Stage IV 6-hour precipitation analysis, both valid on 0600 UTC 7 June 2012.

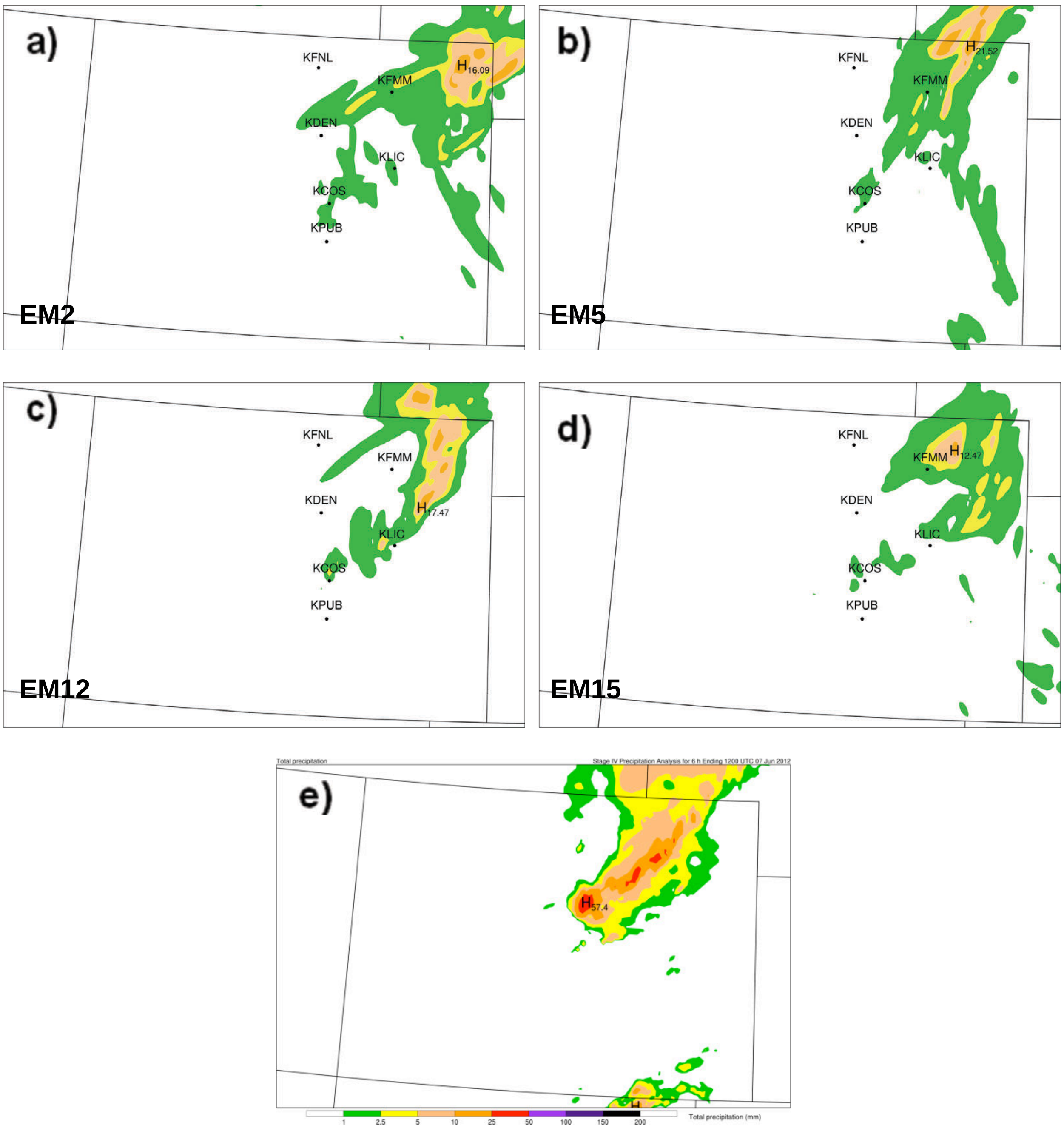


Fig. 3.27: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the "good" members [(a) - (d)], and (e) Stage IV 6-hour precipitation analysis, both valid on 1200 UTC 7 June 2012.

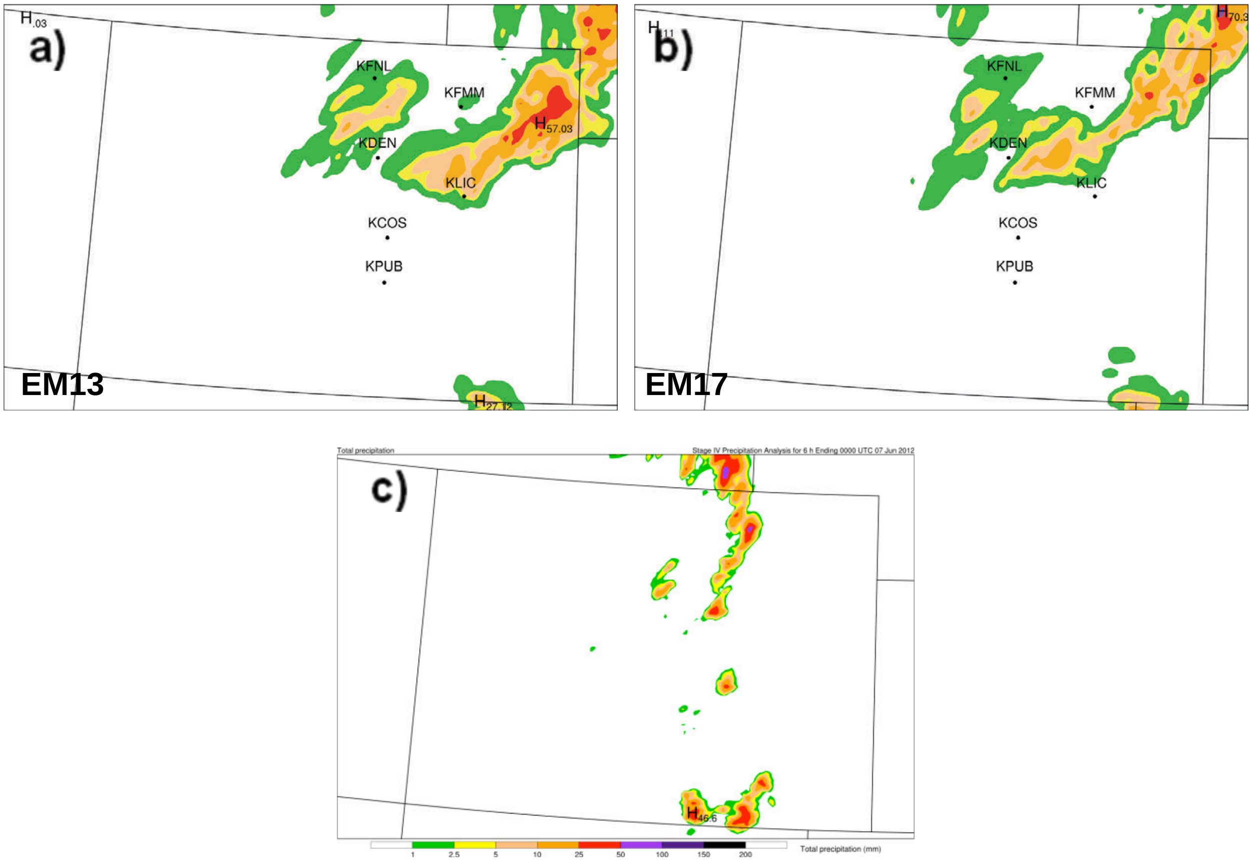


Fig. 3.28: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the "poor" members [(a), (b)], and (c) Stage IV 6-hour precipitation analysis, both valid on 0000 UTC 7 June 2012.

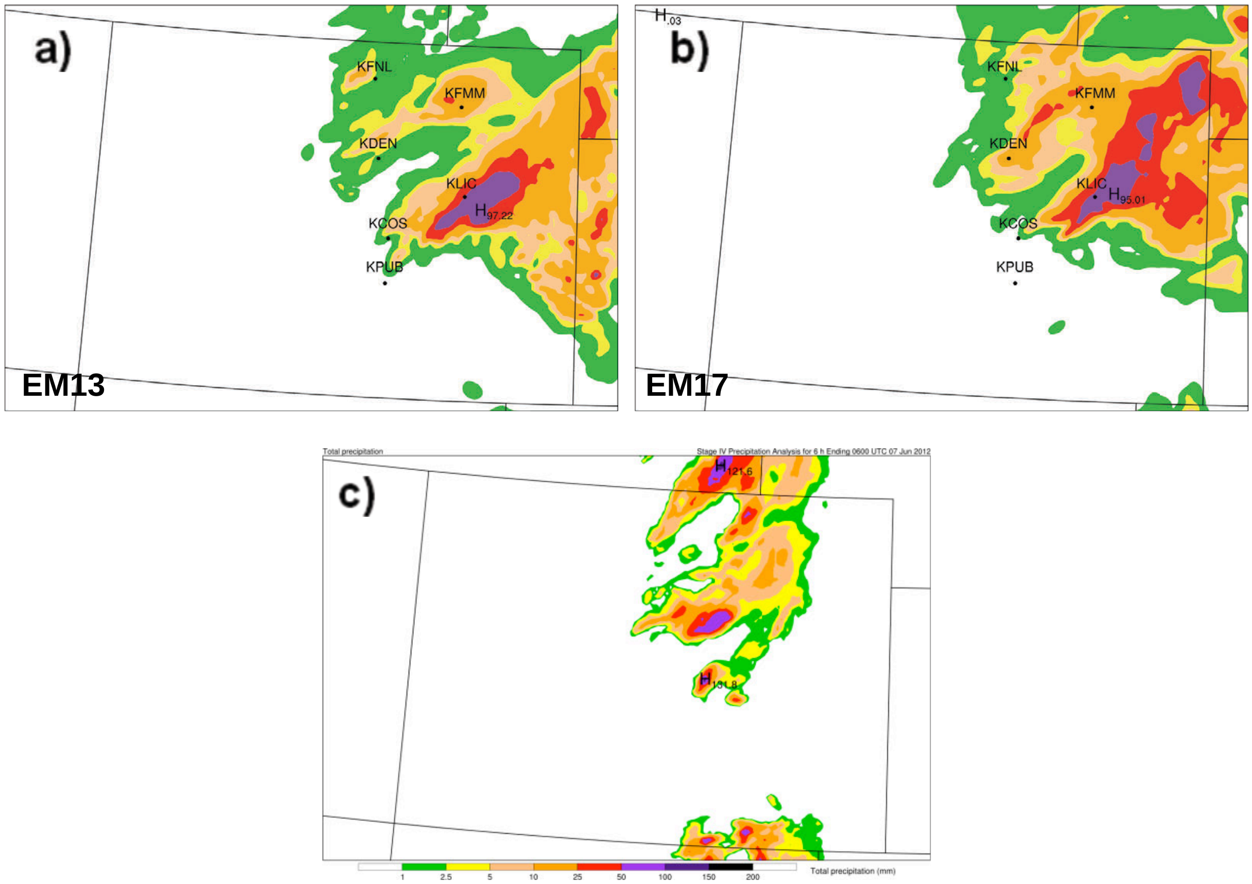


Fig. 3.29: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the "poor" members [(a), (b)], and (c) Stage IV 6-hour precipitation analysis, both valid on 0600 UTC 7 June 2012.

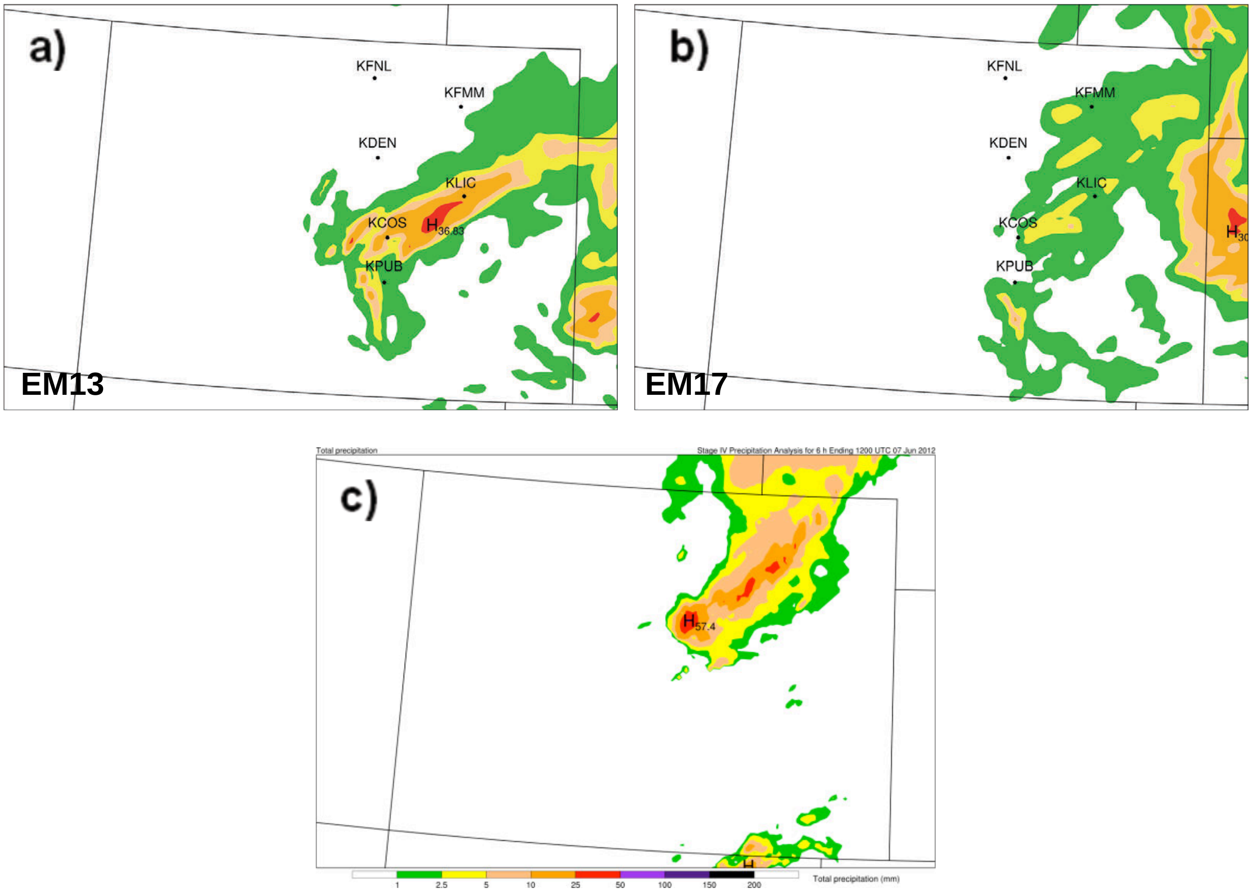


Fig. 3.30: Comparison between the 6-hour accumulated precipitation (mm) forecasts of the "poor" members [(a), (b)], and (c) Stage IV 6-hour precipitation analysis, both valid on 1200 UTC 7 June 2012.

3.3.3 Backbuilding and outflow boundary forecasts

Thus far in evaluating the performance of the "good" and "poor" convection-allowing ensemble members, we have identified two distinct outcomes in relation to convective initiation. The "poor" ensemble members predicted a cold front that moved south far too quickly, initiating convection displaced too far south and east from where it was observed. Conversely, the "good" ensemble members were able to restrain the simulated cold front to the north, and predict a convergence boundary that served as the focal point for convective initiation within the vicinity in which it was observed. Following the development of that convergence boundary were several areas in which backbuilding convection had occurred. As briefly mentioned in the case study, backbuilding convection was observed in the KFTG Denver radar reflectivity (Figs. 2.17b, 2.18a-c) to be associated with 1) the secondary round of convection west of the initial convection along the convergence boundary, 2) the strong, southwest propagation of the Denver convective cell, and 3) the slight southwest propagation of the Colorado Springs convective cell. The clear depiction of backbuilding in the radar imagery motivated further study into whether the "good" ensemble members were able to predict the mesoscale features associated with this backbuilding, as well as to verify its contribution to the propagation characteristics of the two urban convective cells.

Convection-allowing ensemble member #15 was selectively chosen and compared with convection-allowing ensemble member #6 for further investigation on what led to the observed backbuilding convection. The time period considered was between 2200 UTC 6 June and 0200 UTC 7 June. Convection-allowing ensemble member #15 adequately represented the backbuilding convection associated with the initial boundary convection (Fig. 3.31a-e). Although not perfect, the outflow boundary suggested by the streamline to the west of the initial convection at 2200 UTC led to further convective development in that vicinity at 2300 UTC (Fig. 3.31a, b). The same ensemble member also depicted backbuilding convection with the Denver convective cell fairly well (Fig. 3.31c-e). Looking closely, there is indication of an outflow boundary to the south and west of Denver at 2300 UTC, which seemed to have initiated convection in that direction through the rest of the period (Fig. 3.31b-e). The stationarity of the Colorado Springs cell was well captured by convection-allowing ensemble member #15, but not necessarily its propagation to the southwest (Fig. 3.31b-e). Furthermore, there is no indication of an outflow boundary near its vicinity.

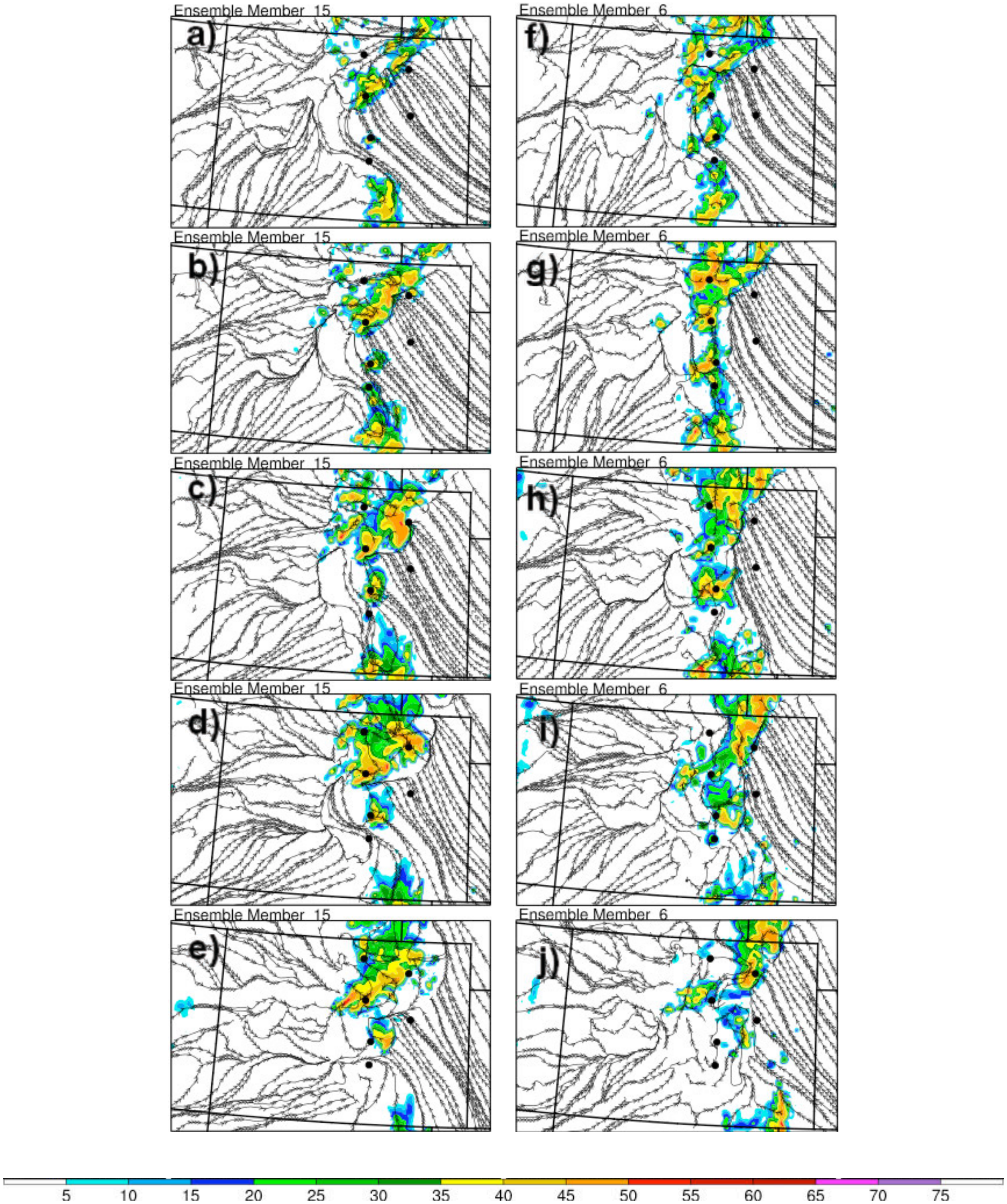


Fig. 3.31: Comparison of the modeled streamline and radar reflectivity analysis between member #15 and member #6 at various time stamps: (a), (f) – 2200 UTC 6 June 2012; (b), (g) – 2300 UTC 6 June 2012; (c), (h) – 0000 UTC 7 June 2012; (d), (i) – 0100 UTC 7 June 2012; (e), (j) – 0200 UTC 7 June 2012.

Although convection-allowing member #6 did a reasonable job at simulating the convective activity along the convergence boundary and near the urbanized areas, it did not provide as clear of a depiction of backbuilding convection in either case. Convection seemed to have quickly organized into a cluster of cells along and west of the boundary (Fig. 3.31f, g), while the simulated convective cells near Denver and Colorado Springs moved east (Fig. 3.31f-j). These comparisons illustrate the significance of the outflow boundaries in the development of backbuilding convection near the convergence boundary and for at least the Denver convective cell. They also support the findings concluded by Liu et al. (2006) and Bernardet et al. (2000) in that explicitly resolving convection can represent the generation, organization, and propagation of convection fairly well. To further support these findings, and attempt to diagnose the behavior of the Colorado Springs convective cell, surface and dewpoint temperature fields of convection-allowing ensemble member #15 were examined.

The 2200 UTC surface temperature field for convection-allowing ensemble member #15 gave some indication of "cooler" air moving northwest and away from the initial convection along the boundary (Fig. 3.32a). This is suggested by the temperature gradient (upper 60s to low 80s °F) across the boundary, with southeasterly winds just to the north and west of Fort Morgan. The presence of this outflow boundary improves by 2300 UTC, where it is outlined by the southeasterly wind barbs pointing away from the leading edge of forecasted convection (Fig. 3.32b). As evident through Fig. 3.32f, g, sufficient moisture (upper 50s °F dewpoint temperatures) coming from the southeast was available for the development and maintenance of convection. The outflow boundary still encountered moisture on the west side of the convection, leading to the backbuilding convection. Another feature that is also present at 2300 UTC is the development of the outflow boundary south and west of Denver, as suggested by the temperature gradient (upper 60s to upper 70s °F) and northeasterly wind just west of Denver (Fig. 3.32b). The cold pool becomes much more pronounced through 0000 UTC and 0100 UTC 7 June (Fig. 3.32c, d). It is likely that this cold pool interacted with the Front Range terrain through moist upslope, as there was still moisture from the south and east feeding in (Fig. 3.32h, i). This acted to generate convection south and west of Denver, characterizing the propagation effect as seen in the KFTG radar observations.

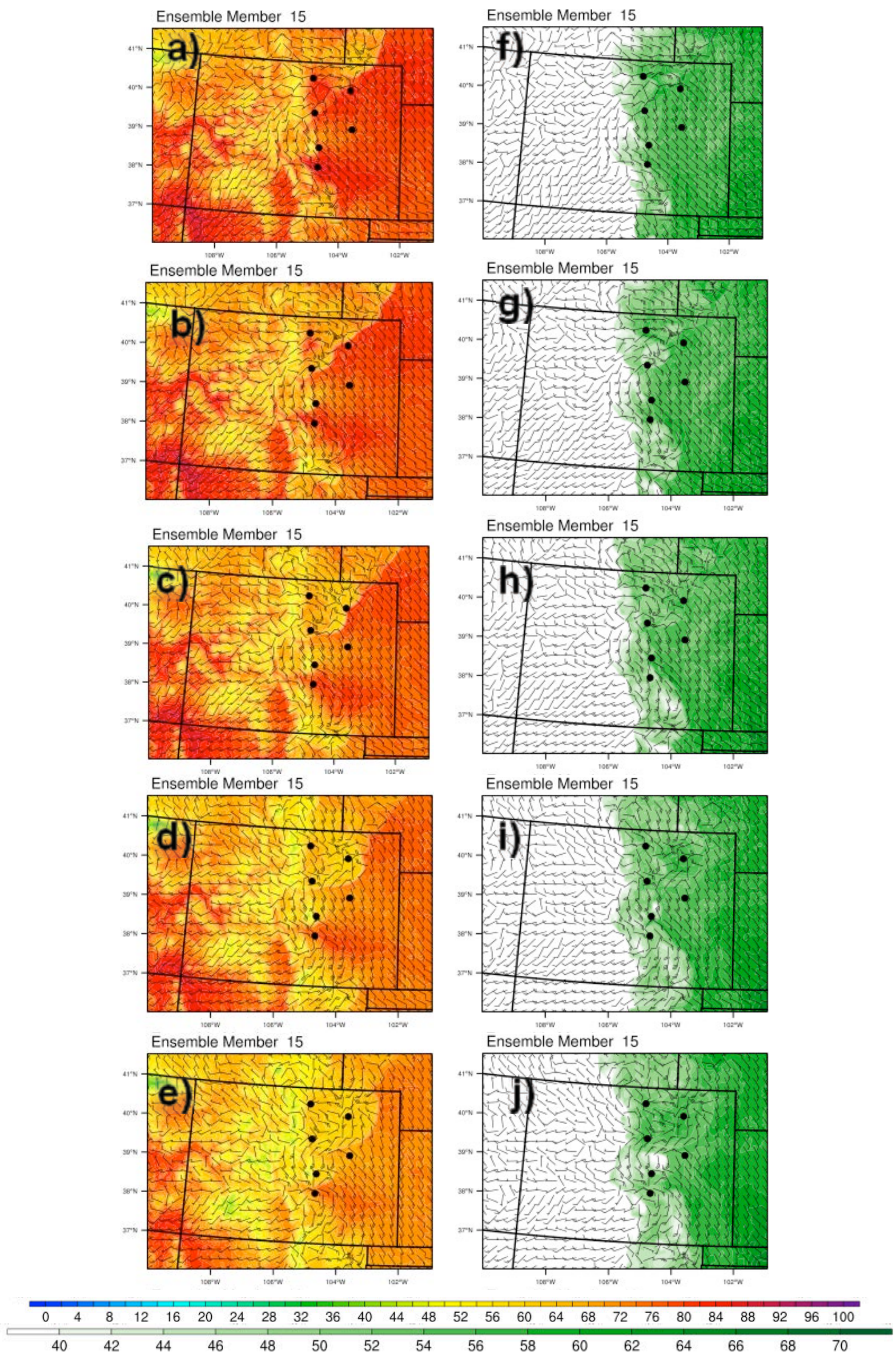


Fig. 3.32: Member #15 forecasts for surface temperature, dewpoint, and wind at various time stamps: (a), (b) – 2200 UTC 6 June 2012; (c), (d) – 2300 UTC 6 June 2012; (e), (f) – 0000 UTC 7 June 2012; (g), (h) – 0100 UTC 7 June 2012; (i), (j) – 0200 UTC 7 June 2012.

As for the Colorado Springs convective cell, there seems to be not as clear of a temperature gradient and wind shift signature that would suggest an outflow boundary moving away from initial convection from 2200 UTC through 0100 UTC 7 June (Fig. 3.32a-d). In this case, it seems as though warm, moist air advection from the southeast continuously fed into the area, likely producing upslope flow over the Front Range and feeding into the convection (Fig. 3.32f-i). However, indications of convective outflow arise by 0100 UTC and continue through 0200 UTC, as suggested by the temperature gradient (low 50s to upper 70s °F) and a northeasterly wind barb just south of Colorado Springs (Fig. 3.32d, e). In combination with decent moisture advection (low 50s °F dewpoint temperatures; Figs. 3.32i, j), this perhaps led to the slight southwest propagation of the storm cell as seen through the KFTG radar observations through this time period.

CHAPTER 4

INTERPRETATION OF HAZARDOUS WEATHER INFORMATION BY FRONT RANGE EMERGENCY MANAGERS

4.1 Introduction

Emergency managers serve an integral role in informing, preparing, and protecting communities in anticipation of hazardous weather that may lead to natural disasters, such as a high-impact precipitation event. The Front Range of Colorado is not unacquainted with such events, as several devastating flash floods have made their footprint in the history of Colorado weather events. There have been several past studies that have investigated how weather information is handled in emergency management decision making. Morss and Ralph (2007) studied how additional meteorological observations from the California Land-falling Jets (CALJET) and Pacific Land-falling Jets (PACJET) field campaigns, which sought to help operational West Coast short-range forecasts, was used by NWS forecasters and forecast users such as emergency managers. How emergency managers integrated forecast information into their decision was described to be fairly complex in this study, and the forecaster-user interactions were found to be of great importance in this process. Weaver et al. (2000) found that emergency managers are able to quickly and accurately assess complex scientific information with the aid of experts from various disciplines (e.g. meteorology, hydrology, etc.). Baumgart et al. (2008) suggested that the most valuable sources of weather information to emergency managers are those that they understand better, have easier access to, or provide them the “big picture”. Both Novak et al. (2012) and Demuth et al. (2013) concluded that emergency managers need forecast uncertainty information that can help them plan for different scenarios, and most often during high-impact events. These studies illustrate the value of weather information to emergency managers, and how it is understood may have an influence on the decision-making processes executed by these individuals. Investigating the steps taken, from when emergency managers first learn about the hazardous weather threat to developing their plan(s) of action, may help us improve the efficacy of how weather information is communicated and used.

The purpose of this component of the study is to examine how emergency managers along the Front Range of Colorado use weather information to lead their decision-making during hazardous weather. Our focus is primarily on the participants' responses to hazardous weather forecasts and uncertainties in a hypothetical hazardous weather scenario. This hypothetical weather scenario takes place during the warm season, as flash flood producing storms are usually convective in nature and occur during the warm season when there is often deep, moist convection (Doswell et al. 1996). In particular, we'd like to know how these users: 1) obtain information about the threat of hazardous weather (i.e. forecasted heavy-rain event) 2) how they interpret this information and 3) their response to that information. To retrieve this information, the study performed in-person interviews with the emergency managers that presented questions on how they gathered, interpreted, and incorporated weather information into their decision-making processes.

The end goal was to increase our understanding of how weather information is distributed and interpreted by emergency managers on days when hazardous weather is predicted over the Front Range area. This part of the study was inspired by the desire to understand how the communication, quality, and uncertainties associated with hazardous weather information influence the decision-making of emergency managers during potentially inclement weather. Whether these forecasts include a high or low degree of uncertainty will sway the corresponding decisions made by these individuals. Learning about the duties, needs, and perspectives of these users will help us gain a sense of how we can improve hazardous weather warning communication, interpretation, and response. In addition, we hope to be informed of any gaps that need to be filled regarding the communication and clarity of weather information to emergency managers, especially in the event of imminent hazardous weather.

4.2 Methods

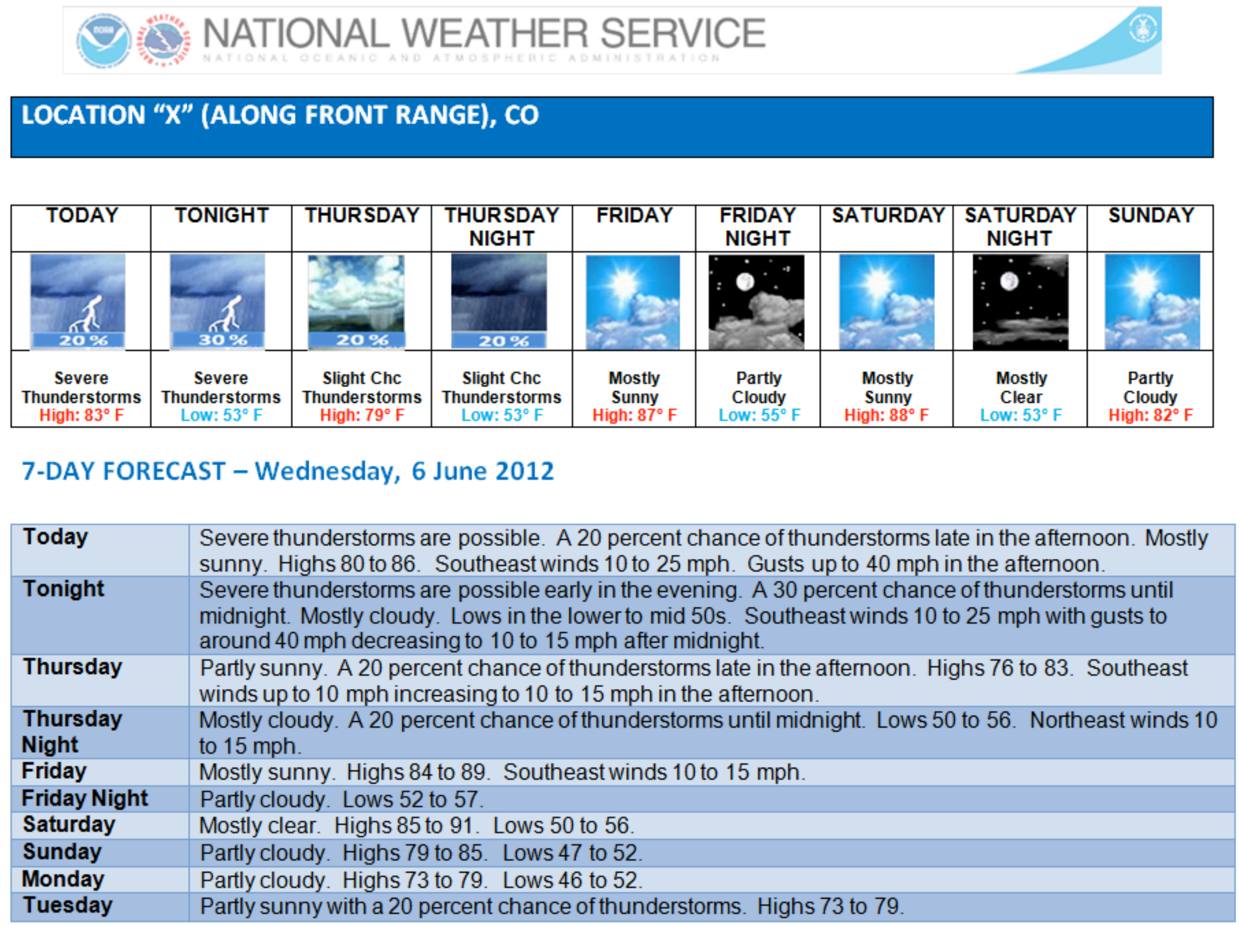
Prior to taking the steps to conduct the human-subject research component of this study, all personnel on the protocol (Principal Investigator: Dr. Russ Schumacher, Co-Principal Investigator Vanessa Vincente) fulfilled the Human Subjects Protection Training. A protocol was submitted to the Social, Behavioral, and Education Research department of the Colorado State University International Review Board (CSU IRB) on 21 December 2012; Protocol # 12-3993H. The title of this protocol was "Use of weather information and decision-making procedures by emergency managers along the Front Range of Colorado under risk for hazardous weather" and was approved on 4 January 2013. This project was supported by Colorado State University I-WATER, a National Science Foundation funded program focused on interdisciplinary water-related research curriculum.

Our subject population focused solely on emergency managers with jurisdictions along the Front Range of Colorado. Such counties of Colorado were subjectively chosen based on their location relative to the foothills and distance from the eastern High Plains. The following counties along the Front Range were considered to recruit emergency managers: Larimer, Douglas, Broomfield, Denver, Jefferson, Arapahoe, and Adams. The contact information of the emergency managers responsible for these counties was publicly available via the following

Colorado Emergency Management website: http://www.coemergency.com/p/local-info-sources.html. Out of the 36 emails sent to the contact list, 9 expressed interest and participated in the interview study. Each emergency manager was sent a consent form via email that described the purpose of the study, its goals, and what the primary investigators would hope to learn from their input. The average time spent interviewing an emergency manager was approximately one hour.

All participants in this study were introduced to a selection of probabilistic weather forecasts. These include a 7-day forecast product issued by the National Weather Service and four other products derived from the WRF ensemble output with explicit convection. In general, these products are separated into two distinct types of forecasts that reflect the perspective used to interpret the weather situation at hand: a point-forecast and a local-forecast. Within the interview, all participants were asked questions related to their background knowledge of warm-season heavy rain events, what weather products they use to learn about the weather, their interpretation of the forecast products provided, and how their work experiences have played a role in their job as an emergency manager. More details related to the questions asked are addressed in the results and discussion (section 4.3).

A replica of the "point-and-click" forecast page, provided by the National Weather Service, served as one of the point-forecasts in the selection of probabilistic weather forecasts (Fig. 4.1). The NWS manages 122 Weather Forecast Offices (WFOs), each of which is accountable for providing forecasts to its geographic area of responsibility, known as its County Warning Area (CWA). These products concern a wide range of aspects such as aviation, fire weather, marine, and climate. The "point-and-click" forecast page provides everyday and hazardous weather forecast information in graphical and textual formats for every 2.5 x 2.5 km grid over land in the United States (Demuth et al. 2013). It contains forecast-at-a-glance out to 4 days or so, and a more detailed 7-day text forecast concerning information on weather conditions, precipitation type and chance of, temperature, and winds. The “point-and-click” weather information used in this study pertains to the city of Colorado Springs, Colorado, which is included in the CWA of the WFO in Pueblo, Colorado, valid at 3:41 am MDT on 6 June 2012. This information was also retrieved from the National Climatic Data Center’s HDSS Access System, which archives numerous text products issued by the NWS WFOs. There is no particular reason why Colorado Springs was chosen as the designated city to retrieve the “point-and-click” information other than it was one of the areas severely impacted by the severe convection on the evening of 6 June 2012.



NATIONAL WEATHER SERVICE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

LOCATION "X" (ALONG FRONT RANGE), CO

TODAY	TONIGHT	THURSDAY	THURSDAY NIGHT	FRIDAY	FRIDAY NIGHT	SATURDAY	SATURDAY NIGHT	SUNDAY
20%	30%	20%	20%					
Severe Thunderstorms High: 83° F	Severe Thunderstorms Low: 53° F	Slight Chc Thunderstorms High: 79° F	Slight Chc Thunderstorms Low: 53° F	Mostly Sunny High: 87° F	Partly Cloudy Low: 55° F	Mostly Sunny High: 88° F	Mostly Clear Low: 53° F	Partly Cloudy High: 82° F

7-DAY FORECAST – Wednesday, 6 June 2012

Today	Severe thunderstorms are possible. A 20 percent chance of thunderstorms late in the afternoon. Mostly sunny. Highs 80 to 86. Southeast winds 10 to 25 mph. Gusts up to 40 mph in the afternoon.
Tonight	Severe thunderstorms are possible early in the evening. A 30 percent chance of thunderstorms until midnight. Mostly cloudy. Lows in the lower to mid 50s. Southeast winds 10 to 25 mph with gusts to around 40 mph decreasing to 10 to 15 mph after midnight.
Thursday	Partly sunny. A 20 percent chance of thunderstorms late in the afternoon. Highs 76 to 83. Southeast winds up to 10 mph increasing to 10 to 15 mph in the afternoon.
Thursday Night	Mostly cloudy. A 20 percent chance of thunderstorms until midnight. Lows 50 to 56. Northeast winds 10 to 15 mph.
Friday	Mostly sunny. Highs 84 to 89. Southeast winds 10 to 15 mph.
Friday Night	Partly cloudy. Lows 52 to 57.
Saturday	Mostly clear. Highs 85 to 91. Lows 50 to 56.
Sunday	Partly cloudy. Highs 79 to 85. Lows 47 to 52.
Monday	Partly cloudy. Highs 73 to 79. Lows 46 to 52.
Tuesday	Partly sunny with a 20 percent chance of thunderstorms. Highs 73 to 79.

Fig. 4.1: Replica of the National Weather Service "point-and-click" forecast page.

The other point-forecast product is the Explicit Ensemble Forecast Plume, which shows a time evolution of the forecasted accumulated precipitation for each ensemble member of the convection-allowing ensemble (Fig. 4.2). Each ensemble member (24 total) is outlined using a distinct color. The varying precipitation forecasts are from a single grid box closest to the forecast point of interest (i.e. the city of Colorado Springs, Colorado). The time series encompasses the 48-hour period on the x-axis at 8-hour intervals from 0000 UTC 6 June 2012 through 0000 UTC 8 June 2012. For the convenience of conceptualizing time and precipitation amounts, this particular product showed time written in local time format on the x-axis and accumulated precipitation in inches on the y-axis.

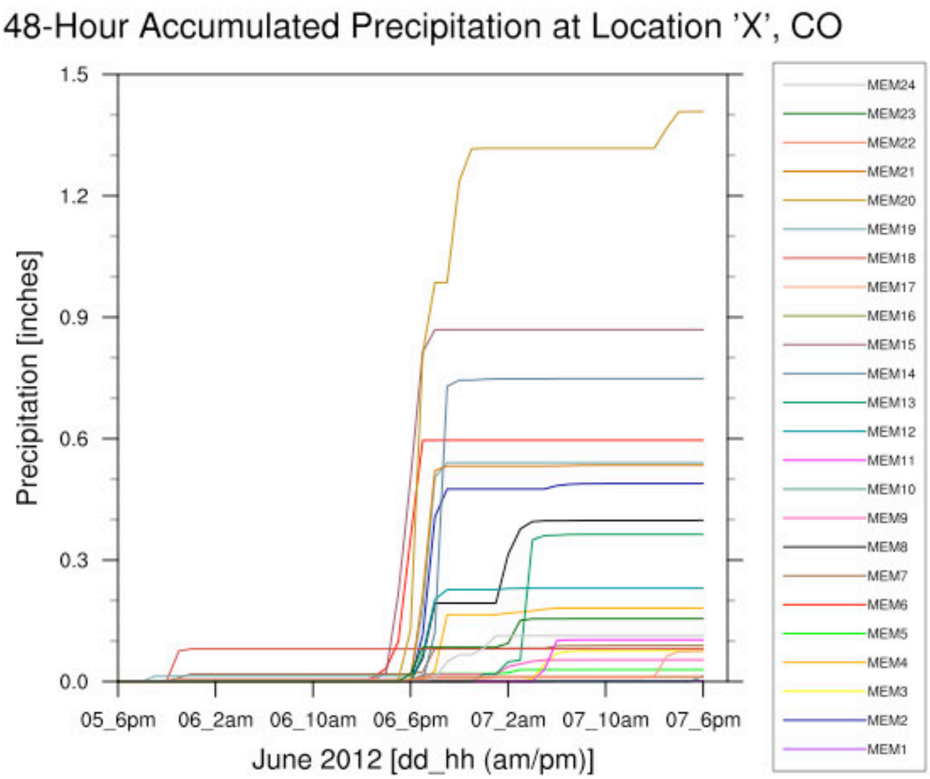


Fig. 4.2: The Explicit Ensemble Forecast Plume, or plume for short.

It is important to note that although these products were point-forecasts for the city of Colorado Springs, the particular location was left anonymous in creation. The purpose of keeping an anonymous profile was so as to not create any bias in the interpretation of the forecast.

During the precipitation event on 6 June 2012, the primary period of activity occurred during the evening in terms widespread convective activity, heaviest rainfall, and hazardous weather impacts. There are two area-forecast products that focused on this particular time period of activity (1800 UTC 6 June through 0000 UTC 7 June 2012) and provided an overview of precipitation forecasts for the state of Colorado. One of these products is the Probability of Exceedence Forecast, which shows the likelihood for exceeding a precipitation threshold predetermined by the user (Fig. 3.16a-c). The probability of exceedence is calculated by counting the number of ensemble members that exceeded a chosen threshold and then dividing by the total number of ensemble members. In this study, four different thresholds of precipitation were incorporated into this product: 25 mm (1 inch), 50 mm (2 inches), 75 mm (3 inches), and 100 mm (4 inches). Again, the thresholds were displayed in terms of inches rather than millimeters. The probability was divided into 6 categories, where progressively shades of blue and green indicated an increase chance of exceeding a particular threshold of precipitation. Additionally, five Colorado cities were plotted on the forecast product: Fort Collins, Fort Morgan, Denver, Colorado Springs, and Pueblo. Each city was identified using a bold back dot and a 3-letter identifier used to represent the geographic city location in terms of latitude and longitude (see Fig. 4.3 and Table 4.1). It is important to note here that this particular product was introduced to the emergency managers after the second interview was conducted. Initially, this product was not part of the selection of forecast representations. However, as probability graphics were requested by the first two participants in the interview process, they were added to the selection of forecast representations.

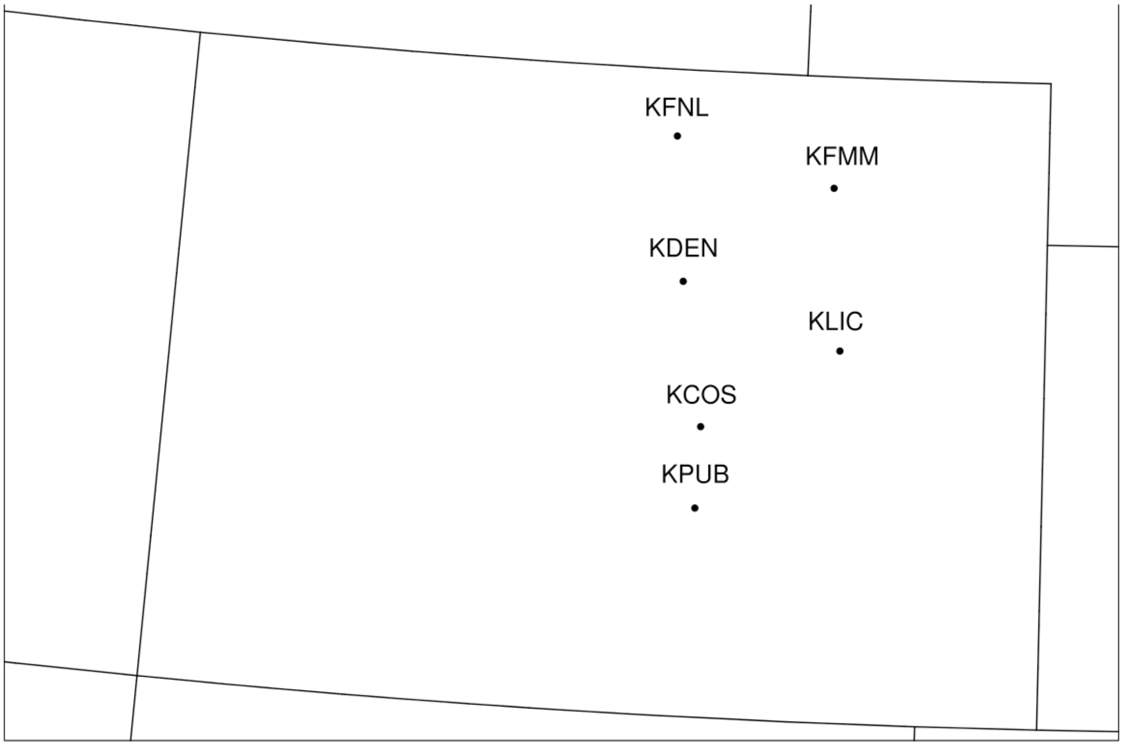


Fig. 4.3: The locations of the five primary Colorado cities or towns illustrated in three of the model forecast products ("point-and-click", probability of exceedence, and 24 6-hour accumulated precipitation forecasts). Each city or town is identified using a bold black dot and a 3-letter identifier. See Table 1 for more details on precise geographic location and abbreviations.

Table 4.1: List of the five primary Colorado cities or towns, their precise geographic location given by the latitude and longitude, and the appropriate location identifier illustrated in three of the model forecast products ("point-and-click", probability of exceedence, and 24 6-hour accumulated precipitation forecasts).

City or Town	Latitude (°)	Longitude (°)	Location Identifier
Fort Collins, Colorado	40.6	-105.1	KFNL
Fort Morgan, Colorado	40.3	-103.8	KFMM
Denver, Colorado	39.7	-105.0	KDEN
Limon, Colorado	39.3	-103.7	KLIC
Colorado Springs, Colorado	38.8	-104.8	KCOS
Pueblo, Colorado	38.3	-104.8	KPUB

The other area-forecast product concerning the most active convective period is a set of 24 6-hour Accumulated Precipitation Forecasts (as in Fig. 3.26, but for all 24 members), which shows an estimate of how much precipitation may fall within a particular 6-hour period. Each member of the convection-allowing ensemble generated a 6-hour accumulated precipitation forecast, hence 24 precipitation forecasts in all. The 6-hour time period, plotted geographic locations, and precipitation unit were also defined to be the same as in the Probability of Exceedence Forecast product. A color table was used to represent the predicted range of precipitation, where cooler colors (green) and warmer colors (yellow, red) were used to denote low and high amounts of precipitation estimates, respectively.

The last area-forecast product is the 48-hour Simulated Radar Reflectivity (example in Fig. 4.4), which was derived from the WRF ensemble model with explicit convection. The 48-hour period was defined to be the same as that in the Short Range Ensemble Forecast Plume product, namely 0000 UTC 6 June through 0000 8 June 2012. A color table similar to that used by the National Weather Service was incorporated into the product as a way to represent the predicted range in reflectivity, expressed in units of dBz. As there were a total of 24 different ensemble members, and each member encompassed a 48 hour forecast of radar reflectivity, a suitable presentation of this product was needed so as to avoid (as much as possible) producing one with overwhelming information. Therefore, this product was presented as two 48 hour imagery loops, each with a set of 12 ensemble members looping through their reflectivity forecasts.

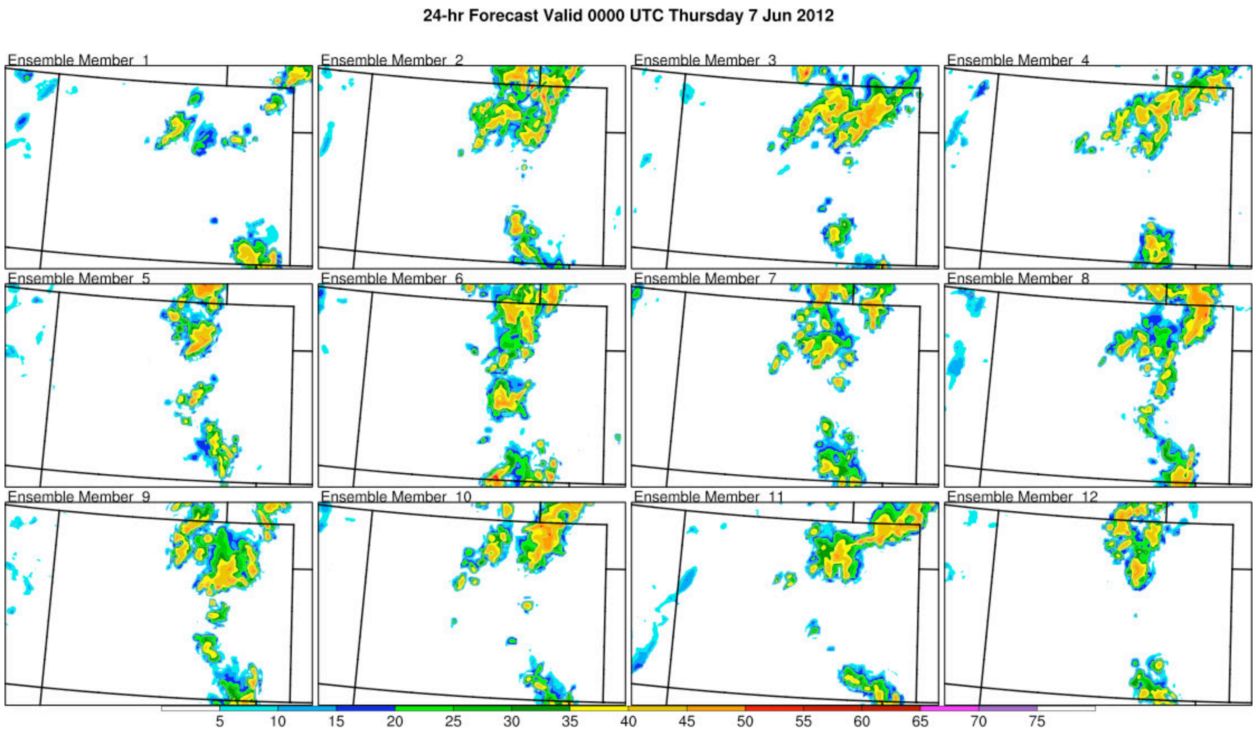


Fig. 4.4: A sample of the 48-hour radar reflectivity loop.

All interview responses were transcribed into separate word documents, each noted with the date of interview as well as a particular participant number that each emergency manager was identified with. The methodology used to interpret these responses was subjective in nature. Each question in the interview script was designated a sheet in an excel workbook, in which the response of each emergency manager corresponding that question was summarized. Then, all the summarized responses associated with a particular question were read through in order to identify common ideas, thoughts, and perspectives between emergency managers. Groups of common responses were color coded and discussed appropriately in the next section.

4.3 Results of interviews with Front Range emergency managers

4.3.1 Background knowledge regarding warm season Front Range convection

Prior to presenting the hypothetical weather scenario, the interviewees were asked a few questions related to the sources of their background knowledge about warm season (June through September, meteorological summer) precipitation events along the Front Range area and what information they would use to assess the behavior of a forecasted heavy rain event. Responding to the former, many of the participants have learned about summer weather patterns in Colorado through the role of being a weather observer. It was through working in the field of emergency management and living in Colorado for many years that these decision makers monitored and surmised common weather conditions throughout the summers in their jurisdictions. The typical origin, direction of movement, and time of occurrence of summertime convection were some of the factors that the participants would notice and record. These observations would serve as a reference guide in which case the emergency managers would have an idea of what to expect and how to respond given that the present weather was similar to a past weather scenario they had experienced before. A couple of the interviewees mentioned using past historical weather events as another reference tool, not only for forecasting what the weather scenario could look like in their jurisdiction, but also to better prepare in planning and warning notifications.

Many of the participants talked about how they received official weather spotter training through the National Weather Service (NWS) and similar courses through the Federal Emergency Management Agency (FEMA). Partaking in such classes gave these decision makers the opportunity to learn or refresh their knowledge concerning Colorado severe weather hazards. Only a few emergency managers have taken minor college-level coursework with a focus on weather and climate; much of the learning has come through training and especially professional interactions with the experts. These relations included various organizations such as contract meteorological services, the Urban Drainage and Flood Control District, and, most commonly, the NWS. Conferences, workshops, and times of hazardous weather are several occasions in which these communications have taken place. During these events, the decision makers can ask questions and get answers concerning diverse topics such as current and forecasted weather scenarios relative to their jurisdictions, imminent weather risks, or understanding current and/or new weather products.

Given that there was a hypothetical threat for a warm season heavy rain event along the Front Range, the interviewees were asked what information they would use to evaluate the situation at hand. There was a diverse range in responses, from smartphone applications and web-based products to situational awareness and collaboration with subject matter experts. Many of the services offered by the NWS are taken advantage of by the participants, illustrating the resourcefulness of the NWS to emergency managers (Morss and Ralph 2007, Baumgart et al. 2008, League et al. 2010, Schumacher et al. 2010). One of the most frequently stated services was the Emergency Management Weather Information Network (EMWIN), a system designed to provide the emergency management community access to NWS weather forecasts, watches, warnings, and other vital emergency information via email or text message. This information is used to keep the emergency managers aware of an imminent hazardous weather event, informed on the latest weather risks, and to help them be proactive in their natural disaster preparation and response procedures. They also access similar reports during conference calls with the NWS in anticipation of ominous weather events, a tool that these individuals are well engaged in and appreciate. In these situations, the emergency managers can have direct contact with the NWS forecasters, listen to their weather discussions, and ask questions to ascertain the uncertainties, timing, and degree of severity relative to their jurisdiction. Other valuable NWS tools, such as real-time radar and satellite, are favored by some of the participants as a way to determine the current weather conditions and monitor their changes locally. A couple of folks may directly contact an NWS forecaster to ask questions and discuss the concerning weather situation. Others recommend taking part in situational awareness by stepping outside themselves and looking for certain weather conditions that, as they have learned through experience, are favorable for a heavy precipitation event in their region.

These decision makers also use several other miscellaneous products that can disseminate NWS warning information to emergency personnel, such as the National Warning System (NAWAS), CodeRED [supported by the Emergency Communications Network (ECN)], Everbridge (a mass notification platform), and the Wireless Emergency Alerts (WEA) program. NAWAS is especially a primary network of communication for key emergency management, law enforcement and NWS units (McCarthy, 2002). Other means of retrieving hazardous weather information included smartphone applications for local news stations, other Internet-based weather services such as AccuWeather and WeatherBug, and basic weather radios. Retrieving information from weather radios during hazardous weather situations is especially important for emergency managers (see Redmond, 1995). Although the NWS was the most popular source for direct access of weather information and alerts, a few interviewees also mentioned the Urban Drainage and Flood Control District (UDFCD) as another basis of weather information, particularly with heavy precipitation. Whether it was through a direct phone call or a receiving a heavy precipitation outlook product sent via email, these decision makers were made aware and updated on forecasts that included potentials for heavy rain events and tracking convective weather.

The participants were also asked what specific weather products they would use to determine how great of a threat the warm season heavy rain event could pose in their region. Much of the emergency managers depend on real-time radar products to provide information on the intensity, projection, and potential hazards associated with the summertime convection across the Front Range area. What they would forecast from the radar data, relative to their jurisdiction, helps shape their reaction and organizes their method of action in response to how the weather may behave. National Weather Service weather radios, model forecasts, and individual forecasters are consulted for precipitation estimates and translation of weather data that either the forecaster or the decision maker is using. As the emergency managers are better aware of the weather situation and understand the potential consequences, such as flooding, activation of the Emergency Operations Center (EOC) may take place and emergency planning is executed. As previously mentioned, a couple of interviewees use products from the UDFCD to have a sense of the probability of the precipitation expected and assess the accompanying weather threats. In particular, these products include the high precipitation outlooks and quantitative precipitation forecasts. However, the majority of the participants rely on the NWS for their information needs.

Emergency managers rely on local weather information to assess the hazardous weather threat on a town or county basis. For this purpose, many of them make use of miscellaneous products that can provide ground truth information concerning the weather situation they are facing. Stream and rain gauge data, field reports, weather observing stations and local news broadcasts all distribute local and regional weather information that the emergency managers use to not only assess and confirm the current weather situation, but also the vulnerability of their jurisdiction. Others look for the environmental cues that suggest an atmospheric disturbance, such as cloud formations and structures as well as changes in temperature, dewpoint and relative humidity. The weather information these decision makers absorb from the media, weather service, or other networks can be reaffirmed by their situational awareness. Establishing such a connection can not only increase the reliability of these sources, but also increase the confidence of these emergency managers in making costly decisions for public safety.

The three primary ingredients necessary to generate an environment conducive for convection are instability, moisture, and a source of lift. Based on previous exposure to summertime Colorado weather events, many of the interviewees identified one or more of these factors as a tool to determine 1) the instability of the atmosphere and its likelihood for thunderstorm development and 2) the hazards that may impact their community and influence their plan of action. As Colorado is known for its dry climate, many of the emergency managers would relate a notable change in atmospheric moisture content with greater potential for afternoon thunderstorms that may bring heavy precipitation. They would focus on their feeling of moisture, or look for changes in dewpoint or relative humidity as indicators of moisture gradients. A couple of the decision makers acknowledged the North American Monsoon as the chief transport for moisture to the Front Range area. This phenomenon had been used in the context of relief for Colorado's wildfire season as well as the fuel for heavy rainfall, both concerning issues in the emergency management community. The participants have also related changes in surface temperature and wind direction to sources for lift, such as with a cold frontal passage or upslope flow over the Front Range. The emergency managers recognize these lifting mechanisms, in combination with great atmospheric moisture and instability, as a prime set-up for an active afternoon. This relationship is commonly diagnosed and understood by these participants after years of experience with Colorado weather patterns. As one emergency manager said:

"… I understand a little more after doing this for 8 years, I understand a little more as to what that's really like. You can even go outside and I go 'hmmmmm' cause you get a feeling. You can tell, you know, by the level of the moisture in the air or something, or the quick drop in temp that, you know, some-something's happening and depending on that change, you start getting those gut feelings. And part of it I think is cause you, you've been there before and seen it."

In a situation where there is a potential for heavy rain producing thunderstorms, emergency managers always consider the vulnerability of their jurisdiction to such a high impact event. One of the participants described how investigating the characteristics of the storm system taking place helped them assess the weather situation, project the outcomes, and decide how best to plan for the impacts. The history of the storm (i.e. past behavior) as well as its movement, speed, and projected path are all factors taken into account. Other participants give attention to the direction in which the storms are coming from, which could help them determine the populations in their jurisdiction most at risk to face the impacts.

4.3.2 Role of forecast uncertainty in understanding forecast products

One of the primary goals of this study is to learn about the meaning of forecast uncertainty through the lens of an emergency manager. Although these responses have been treated through subjective analysis, it seems as though the participants had approached the question in either one of two perspectives. That is, their approach has been identified as either in a qualitative or quantitative sense.

Most of the emergency managers perceived forecast uncertainty in a qualitative sense with an understanding that forecasting the weather is an imprecise science. As simply stated by one participant “Mother Nature can be fickle”. The chaotic nature of our atmosphere and the variables forecasters use to characterize its complex behavior are widely acknowledged by these decision makers. For example, a couple of the participants had mentioned how local forecasters are challenged by the interactions between the Front Range terrain and passing weather systems. Such relationships at this interface exemplify the level of difficulty in not only predicting the weather conditions at any particular time, but also generating precipitation forecasts for the Front Range area. Interestingly, one of the emergency managers mentioned that his jurisdiction was not as vulnerable to heavy rain events as other neighboring jurisdictions are, and that their area is more impacted by winter storms than warm-season heavy rain events. Despite their vulnerability to a particular weather phenomenon, it did not seem to influence their perspective that forecast uncertainty dealt with imprecision.

Numerical weather prediction is relied on greatly by forecasters to produce quantitative precipitation forecasts. These systems use a variety of parameterizations in order to appropriately predict the future state of the atmosphere. As different models can be designated different parameterizations, forecasters are provided a range of possible weather scenarios. These models have been described by many of the participants as a way to rate the uncertainty of a particular weather situation and to accept the possibility that any forecast can be misleading. The fact that numerical weather models cannot accurately predict the timing, location, trajectory, and amount of precipitation is well acknowledged by these decision makers. The variability presented within forecasting these characteristics for any forthcoming weather system is something admitted by the interviewees; it seems that they perceive these forecasts “with a grain of salt". It seems as though they have adopted a direct relationship between forecast variability with confidence; the greater the unpredictability of the weather situation, the more uncertainty there is in its impact and the less confidence there is in providing an accurate forecast. There is an imperfection to operational forecasting that has taught these decision makers to be prepared and stay on alert, as the weather situation can change at an instant and they would prefer not to be caught off guard/taken by surprise.

Other emergency managers viewed forecast uncertainty in a quantitative sense, using percent values as a reliability tool to know the likelihood of a particular occurrence. For example, knowing the probability of an event happening versus not happening gives them a sense of the uncertainty for that situation. A similar concept was also described as a forecast having a 'plus or minus window', where a particular weather event can go in one of two directions. This can be interpreted as the outcome of a particular forecast verifying or being a false alarm. In either case, uncertainty exists in the probability of a forecasted weather event actually happening; there is the probability of a correct forecast. These uncertainties, as expressed by one participant, are illustrated into precipitation forecasts as a range of potential amounts rather than a precise amount.

A majority of the interviewees decipher forecast uncertainty through reading the forecast discussions or weekly forecasts provided by the National Weather Service. They seem to gather the uncertainty from two different sources that communicate this type of information: 1) percent chance (quantitative) and 2) keywords that relay ambiguity, such as "chance of" (qualitative). These discussions allow the decision makers to follow the forecasters' train of thought concerning the weather event at hand in terms of how the storm *could* behave and what *could* be expected. Despite the doubt in their forecasts, these participants have trust and a sense of reliability in the forecasters themselves, knowing that they are being given quality information to the best of the forecasters' judgment. Similar attitudes are shared by a couple other emergency managers that use a different resource, such as services provided by the Urban Drainage and Flood Control District and Public Works.

Situational awareness is another popular quality following how these participants appraise forecast uncertainty. A few of the decision makers prefer to keep themselves informed in advance of what is expected, using what they know is typical of summertime convection (e.g. thunderstorms tend to develop off the Front Range) and observing the skies for signs. One emergency manager disliked the use of text forecasts and instead preferred to independently study time-lapsed modeled forecasts. Living in Colorado for many years has helped them grow that 'gut feeling' used to differentiate between everyday and unusual weather conditions. They have also learned to be vigilant of how the weather is impacting neighboring areas so that protocols can be in place within their own jurisdictions beforehand. As one participant stated:

"I don't think we have luxury of, um, casting aside uncertainties in thinking that there's no need to concern ourselves. I think that we need to really keep our, um, our eyes open because the weather here is so dynamic."

It is a common action between many of the decision makers to compare weather information and uncertainties they gather from various local news stations. The competitive nature and habit of producing startling or thrilling impressions are characteristics of the media that a couple of these participants believe to be true. For this reason, there is a certain level of trust or credibility that the newscasts need to build and grow in their relationship with the emergency managers. Although it may be easiest, quickest, or most convenient for these individuals to learn what the weather situation is from the broadcasters, some take the extra step to further assess the situation relative to their jurisdiction. Relationships with their contracted local meteorologist or the NWS forecasters are considered an important and valuable resource, a similar finding associated with the emergency managers interviewed by Morss and Ralph (2007, Baumgart 2008). These participants can ask specific questions about the potential hazardous weather risks relative to their locations, information that can be much more helpful and useful compared to the broad and sensational version provided by the media. It seems that often times there is a 'teacher-student' environment in place, where the students (emergency managers) inquire and build their understanding of weather and forecast uncertainty through the mentoring of the teachers (mainly the NWS). The students have trust in the quality and reliability of information given by the teachers. In turn, the assignments or exams (hazardous weather events) allow the students to apply what they know and learn from their mistakes (past planning experiences) to be better prepared for what is next.

Following the discussion on the personal understanding and discovery of forecast uncertainty was the introduction to the hypothetical weather scenario. As previously mentioned, the Colorado Springs rain and hailstorm event served as a hypothetical weather scenario in which case five different forecast representations were generated from the convection-allowing 24 member ensemble output. The purpose of presenting these products to the emergency managers was to learn how forecast uncertainty and general weather information was received and understood, with a focus on how well the potential for flooding was communicated through these products.

The interviewees provided great initial thought and comment regarding several aspects of the forecast products such as appearance, quality of information, and potential modifications to tailor their needs. All of the participants were most familiar and comfortable with the NWS 7-

day forecast out of all products. This is not a surprising observation given the close relationship and interaction between the local NWS and these decision makers. Many of the emergency managers also felt that this particular product was very useful in providing them a decent general overview of the current and future weather conditions. The ability to quickly learn about the weather using a product that was simple and generic in format was well commended. Several terms were used to describe the basic nature of this particular product, such as “broad brush”, “bread and butter”, and “dashboard”.

One of the first pieces of information the participants gave attention to was the sense of probability or percent chance as indicated in both the weather icons and text description of the NWS product. Most of the interviewees interpreted probability as the likelihood of a particular event actually happening, where there is a direct relationship between the forecasted percent value and the confidence the emergency managers have in event occurrence. At least one emergency manager alluded to integrating what they surmised from past historical weather events into their personal judgment of probability. Although this asset cannot assume to be true for all decision makers, it does add value to how emergency managers interpret the forecasts. That is, without a probabilistic forecast, there is no baseline from which these emergency managers can compare their experiences with in order to grow their personal judgment of probabilistic precipitation forecasts.

The 24 member 6 hour ensemble forecast product was favored by most participants as a useful way to learn what areas may receive precipitation and also how much. The variability in precipitation as characterized by the color scale, as well as the location identifiers, provided great ease in retrieving valuable pieces of information. Such information included differentiating areas that may receive heavier versus lighter precipitation, determining vulnerable areas at risk for flooding (e.g. burn areas), and knowing where the precipitation may fall relative to their vicinity. On the contrary, there was a couple of other emergency managers that disliked this particular product, and in a contradicting sense. While one emergency manager felt the product was overwhelming, likely due to the sheer volume of information, another felt a lack thereof in that there was no probabilistic reference to each member. Probable solutions suggested were 1) to blend, or average, the precipitation forecasts into one image and 2) for each member to carry a likelihood of occurrence expressed as a percent value. These observations illustrate the diversity in perception, opinion, and need of the decision makers in understanding and making use of precipitation forecast products.

As with the 24 member 6 hour ensemble forecast product, most interviewees were also fond of the 48 hour simulated radar reflectivity product. Many of them found the modeled radar to serve as a practical tool for not only knowing the potential initiation point and trajectory of convection, but also for incident planning concerning community events or wildland fires. Given the advantage of observing where the convection may start and where it may go provides these decision makers time to prepare and plan ahead for any impending natural disasters. Such a tool would be useful for municipal planners, as was stated by a couple of the participants. As previously discussed, many of the interviews understand that the nearby mountain range can play a major role in thunderstorm development. Seeing this phenomena projected in the modeled radar can create a genuine perspective into the precipitation forecasts provided by the NWS.

There were a couple of emergency managers that did not like the simulated radar product. One participant felt the product was overwhelming in the sense of being presented with too much information, and suggested they would prefer a single compiled image that represented the “tip of the bell curve”. Another participant did not care much for the product as he felt it has led him astray in the track of the convection. Understanding the inaccuracy of the simulated radar, they did offer to use the product if it was able to forecast at shorter time scales. Similar to the former participant, they too preferred an overall picture of where the heaviest precipitation could be, information that can be drawn from the 6 hour ensemble forecast product (which was a product they liked). In addition, a couple of the emergency managers expressed confusion about what exactly was represented in the simulated radar product in terms of the timing. It is possible that not all the emergency managers understood the purpose of this product, understood what it was showing, or considered its potential as a forecast product. That is, they may have said they liked the simulated radar reflectivity without really grasping what it entailed.

Mixed reviews concerning the 48 hour forecasted precipitation time series (i.e., plume) product was received by most of the interviewees. The majority felt that the product was not tailored to their needs; either it consisted of too much detail than desired, did not provide an immediate overview of the weather at hand, took too much time as it was obscure in context, or was beyond the scope of their understanding. In turn, these participants felt that this particular product was either frustrating to use, served as the last resort for information, or would be completely ignored all together. On the other hand, there were a couple of emergency managers that liked the product as it gave them a sense for the probability and timing of the likelihood for precipitation and when to expect the heaviest amounts, respectively. Such information was drawn from their personal interpretation of the behavior of the lines that represented each forecast member. Furthermore, a couple of interviewees noticed the ‘clump’ nature or similarity between the model runs. This may be perceived as their effort in determining the level of agreement between model runs, introducing them to a new and fresh method to understanding forecast uncertainty.

Lastly, most of the participants liked the probabilistic precipitation forecast product. The quick visual of the forecast and its simplicity in presenting information regarding where precipitation may fall and estimated amounts were among the modest comments received. At least one emergency manager would have wanted a similar probabilistic forecast for certain types of precipitation, as well as shorter time scale forecasts so as to plan for any anticipated concerns. Otherwise, not much feedback was given with this product. This is not too surprising, as its simple yet informative character would be a quality that satisfies the urgent needs of these decision makers.

Given the responsibilities of an emergency manager during times of hazardous weather, it is to their advantage to make use of products that promptly provide quality weather information. The participants of this study were asked to estimate how much time they would dedicate to using the products presented to them. Interestingly, it seems as though the time the interviewees' spent on the products depended on either 1) the weather situation they were facing or 2) the quality of information they were able to retrieve from a particular product. For a couple of those that followed the former, a potential for precipitation in the forecast meant just that, *a potential*; the products would be given a glance. However, if the threat for a precipitation event was high, or an event was in progress, more time would be devoted to those products. There would also be an additional factor that may act to enhance the significance of or concern for the event, such as confirmation via situational awareness or knowing the effects of a recent burn area. A few other decision makers may have focused more on how a precipitation event, either forecasted or in action, would impact their jurisdiction. Relative to its severity and trajectory, more time would be given to frequently review the products throughout the day for any changes in the forecast. The rest of the participants that followed the latter suggested mixed attitudes towards using some or all of the products. The NWS 7-day forecast was considered to be used anywhere from one minute to half an hour. It is possible that the time varied on its use because this product is very familiar and generic to these emergency managers, and depending on what information or how much detail they are looking for controls how much time they spend. As for the 6 hour ensemble forecast, no time was spent due to the overwhelming amount of information and lack of probability, or it would be frequently reviewed in the effort to gain an understanding. The first impression the emergency managers had on the 48 hour time series product, which most were newly introduced to, seemed to have determined whether they would take any time to use it. For example, while one emergency manager would not use the product at all, perhaps due to the chaotic nature of the lines, another found that characteristic as a way to confirm someone was going to get precipitation and also how much. For those that commented on the simulated radar product, it was concluded that these particular participants would not use the product, and for various reasons: 1) they relied on another meteorological service that shared their expertise 2) they felt confident in themselves to predict the progress of the storm with time or 3) was already adapted to using the observational radar system as a way to forecast storm behavior. The probability product was given the least remarks, with just a couple of the interviewees mentioning that they would give it a quick glance or two throughout the day.

Given the first impression and how much time would be dedicated to understand the purpose of each forecast product, the quality of information drawn from them all together was also studied relative to the particular event. While many of the participants generally reiterated what they could learn from each product, most provided detailed information related to the meaning of the forecast. For example, many of the interviewees identified the timing of peak activity for precipitation to occur during “dinner time” or “rush hour”, likely referring to the early evening hours (6 pm LT), on 6 June 2012. A couple of participants even observed this time of peak activity as illustrating the typical afternoon thunderstorm period in Colorado. Furthermore, a few emergency managers acknowledged the risk for hazardous weather as they saw the potential for heavy rainfall over a general threat area. Some of these individuals made the effort to identify targeted locations, particular rainfall rates or amounts. Such examples include the potential for 1.5 inches $hour^{-1}$ in the eastern plains of Colorado, 4 to 6 inches or rain over broad area, or greater than 1 inch in northeast Colorado with embedded areas possibly receiving greater than 2 inches. Overall, it seemed as though the conclusions discussed herein were focused on precipitation characteristics and were gathered from a combination of the 24 member 6 hour precipitation forecast, probability of precipitation, and 48 hour time series products. Although these decision makers are most familiar with the NWS product, it is likely because of the generality in the 7-day forecast that they were unable to derive further details concerning the timing, amount, and spread of precipitation. There are other services provided by the NWS that provide this information, such as the hourly weather graph and quantitative precipitation forecasts. However, these sources were not considered in this study. Additionally, the participants often discussed the simulated radar product in the sense of what they could use it for and not for what information it presents to them. At least one emergency manager found that storms were developing in parts of northeast Colorado, and were moving in an east/northeast direction. Since observational radar is commonly used to monitor convection and forecast its behavior, as well as using their own instincts, they may not feel the great need to use the simulated radar product for similar tasks.

The Colorado Springs severe thunderstorm produced as much as four inches of rain and hail over the eastern part of the city, which led to significant street flooding. As this event was presented as a hypothetical weather scenario, the interviewees were asked if they saw information from any of the products that led them to believe there was a risk for flooding. This question was intended for the emergency managers to condense the information they gathered from the forecast products and determine the likelihood for flooding, if any. Attention was directed towards the participants being able to identify a possibility for flooding to occur more so than the location in which the flooding may take place. This is because two out of the five forecast products were specifically relative to an anonymous location along the Front Range of Colorado while the others focused on the state as a whole; this may not have been sufficient information for the participants to use to determine the precise location for flooding. Furthermore, even if any of the decision makers felt there was no obvious risk for flooding, it was of interest to observe if they would at least recognize the imperfections of precipitation forecasts and consider the possibility of flooding regardless.

Most of the interviewees in this study firmly believed that there was a high probability for flooding, using background information from one or more of the forecast products to support their answer. As previously discussed, the generality of the NWS 7 day forecast product is held responsible for providing inadequate information related to quantitative precipitation forecasts, such that the emergency managers did not feel confident enough to determine any risk for flooding. The simulated radar product was referred to by at least one participant as an indicator for flood potential, given that the ensemble forecasts showed precipitation falling over an extensive area. The 24 member 6 hour ensemble forecast was considered most efficient at directly illustrating concerns for flooding. This is because the variation in the color scale used to classify the various amounts of forecasted precipitation translated to the degree of forecasted precipitation intensity, thereby informing these decisions makers of areas that may receive lighter versus heavier rainfall. Interestingly, both the 48 hour accumulated forecast precipitation and probability of precipitation product received mixed reviews on whether or not it suggested any risk for flooding. For those in favor of the former, the risk for flooding was inferred from the sharp "jump" in forecasted precipitation amount at approximately 6 pm on 6 June 2013. However, there was some confusion on understanding the relationship between the forecasted precipitation amount and time in hourly increments. A couple of the participants described the risk of flooding in terms of an hourly rate of precipitation as opposed to an accumulation of precipitation within a particular time period. Nevertheless, the idea that there was sudden increase in precipitation within a short time period indicated the likelihood for flooding. Additionally, a couple of others that did not process well the information from this particular product (and therefore were inconclusive to the risk of flooding) were substituted by the probability of precipitation product. These emergency managers acknowledged that accumulated precipitation may lead to clogged drainages, landslides attributed to burn areas, or debris flows, all of which are possible impacts from flooding. This is an example of using prior knowledge and experience as a guide to their interpretation and response to hazardous weather information.

There were at least two interviewees that did not see a risk for flooding, and commonly attributed it to two factors: 1) the low probability for thunderstorm occurrence and 2) the notion that relatively little rainfall will come out of it. Although one of these participants supported their theory by discussing the forecasted steady movement of convection, they still gave the benefit of the doubt. Stating the current drought conditions, their unfamiliarity with Colorado's eastern plains, and knowing the downstream affects of mountain convection led them to the slight possibility for flooding, but still stood firm in their response. The other emergency manager did inquire about ground conditions, particularly relating to burn areas, but also stayed firm in their answer. The participants were not in a wrong position for thinking this way, given that the probability of exceedence and 6-hour precipitation accumulation products showed the potentials to be highest out on the plains rather than along the urban corridor.

One of the future goals in this study is to generate forecast products that effectively convey future weather conditions, especially its uncertainties, to decision makers across the Front Range area. The purpose of presenting the five experimental forecast products was to not only observe if and how emergency managers understand the weather information and its potential hazardous, but also the associated uncertainties. The participants were asked if they perceived any uncertainty in the different forecast representations; most confirmed this assertion. For these respondents, many shared the idea that there is an inherent uncertainty that follows modeled forecasts; within the science of predicting the unknown, there is the uncertainty and therefore there is a hypothesis. As one participant acknowledged:

"…the key thing for me to understand when it comes to weather forecasts is that it's all… based on science and history and… all these other factors, but when it comes right down to it… it's an educated best guess".

In addition, they also identified certain characteristics of one or more of the forecast products that suggested uncertainty in the forecast. Forecast uncertainty was perceived in a few different ways by those that commented on the NWS 7 day forecast product. While one interviewee found it challenging to see the uncertainty of the forecast given the generality of its presentation (and that it presents the most likely), another judged the uncertainty based on the "chance of" (expressed as a percent, where the odds were weighed). At least one other participant saw uncertainty later in the forecast, as they felt short-term environmental conditions (e.g. saturated soils and changes in humidity) could influence the projected weather pattern then.

Mixed views also followed the 24 member 6 hour forecast product from the respondents discussed in the previous paragraph. While one emergency manager felt that the similarities between the different precipitation scenarios suggested little uncertainty in the forecast, a couple of others thought just the opposite. They attributed the dissimilarities, lack of not knowing the "mean" or average scenario (likely referring to the most probable), and other characteristic details such as the intensity and speed of precipitation, to the uncertainty of the forecast. Similar patterns followed the simulated radar product, where the participant who perceived similarities between the 6 hour forecast precipitation scenarios shared the same idea with this particular product. Interestingly, he saw uncertainty in the amount of precipitation that is suggested by the modeled radar (a factor that is estimated from radar and has its limitations). Meanwhile, the other two interviewees once again recognized uncertainty, and in different perspectives. One emergency manager identified ambiguity in the track and targeted locations, but sincerely would not put forth the time nor effort in applying that uncertainty due to the sudden abundance in information presented in the product. The other decision maker felt uncertainty in the sense that he was not able to monitor predicted convective activity beyond the Colorado domain, a capability he considers to be significant in his long-term planning for anticipated weather hazards in his jurisdiction. The observations discussed above illustrate how the initial approach to interpreting these forecast products (either broadly or meticulously) can influence the perception and reading made by the user.

Although a couple of the respondents responded to the 48 hour accumulated precipitation product, both shared common ground in that the variability of forecasted precipitation produced by each ensemble member (as illustrated via the behavior of the lines) stresses the uncertainty as a whole. Interestingly, the interviewee that would not make use of the uncertainty in the simulated radar product shared the same view towards the 48 hour accumulated precipitation product. They did see an agreement in the forecasts in terms of the initiation for precipitation, but that feature may have been overcome by the clutter of the lines. As a side note, this was also the only decision maker that commented on the probability of precipitation product in terms of forecast uncertainty, but yet again faced difficulty in making sense of what they were seeing in the product. It is thought that the unfamiliarity and volume of information some of the forecast products may have for these emergency managers may be incompatible or unsuitable with the great responsibilities and time constraints their profession holds, at least for this particular participant.

There was only one interviewee that did not observe much uncertainty in the presented forecast products. As perceived by the participant, there was no sense of improbability in the simulated radar product and the 48 hour accumulated precipitation product expressed confusion, as the odds of each scenario was unknown. The emergency manager distinguishes the imperfection of general weather forecasts but instead of *observing* it as uncertainty, the probabilities expressed in these forecasts already have an *inherent* uncertainty. It is believed that this participant's train of thought relates to the fact that users should not take precipitation forecasts at face value, as the science has yet to reach the point where the timing, location, and intensity of precipitation can be accurately forecasted. As a result, precipitation cannot be predicted with a probability of 100%. That is, because it is not possible to predict with 100% certainty, the percent value placed on the forecast does not matter as much.

Following the analysis of the forecast products, all interviewees were asked to provide critique in terms of how easily the weather forecast information was presented. Overall, most of the participants found the forecast products to be relatively clear and easy to understand; half of these cases found the 48 hour accumulated precipitation product to be an exception. As previously mentioned, it is likely that the unfamiliarity, detailed impression, and required time it would take for the emergency managers to understand what information is involved makes this product not so well eye-catching. However, this observation cannot be assumed for all decision makers, as there were a few others that were able see through the complex appearance of the product and grasp the main features. Another noteworthy observation is the caveat that some decision makers implied directed to the similar radar and 24 member 6 hour forecasted precipitation products. Although both of these products offer valuable information in terms of projection and intensity of convection, the idea of having 24 possible outcomes did not sound appealing; it's a stipulation one has to consider when using these types of products. There was at least one interviewee that generally found some difficulty in understanding the forecast products, particularly with the 48 accumulation and 24 member 6 hour forecasted precipitation product. The fact of not knowing the likelihood of each scenario yielded a sense of subjectivity to this participant, and instead would prefer a summary of the key findings (discussed later).

The emergency managers were also asked which forecast products they felt were the most visually pleasing, and if they had any suggestions for improvement on how one or more of the products relayed weather information. The responses varied as the decisions makers chose either one, a select group, or all products as overall gratifying. Reports of positive feedback included how weather information was effectively communicated through the basic language of the NWS product; the simple design of the 24 member 6 hour forecasted precipitation product in showing the geographic distribution and amount of rainfall over a given period of time; and the immediate signature displayed by the members in the 48 accumulated precipitation product that indicated the timing and amount of precipitation during peak activity (which is just a coincidence). A few participants did describe a few visual flaws that they believed were a part of a given product. Examples include being distracted with the certainty and losing focus on the uncertainty in the 48 hour accumulated precipitation product, or the need for greater gradation in the color scheme of the probability product. Putting these comments to the side, it seems as though these interviewees would be open to using one or more of the forecast product for their everyday weather briefing. Each forecast product is structured in a way that helped to illustrate one or more significant hazardous weather features; it is whether the decision maker has the patience, willingness, and desire to make use of them.

Various propositions were stated by the interviewees that either related to the forecast product themselves, or adding supplemental weather information. Concerning the former, a few of the participants would have appreciated if probability was associated with each scenario in the 24 member 6 hour forecasted precipitation product, 48 hour accumulation product, and the simulated radar product. It was learned in this study that often times emergency managers consider the worst possible weather scenario, and prepare for the case that has the greatest potential to occur. Therefore, it would behoove these decision makers to be provided with forecast products that “rank” the probability of each possible weather outcome, from “least likely” to “most likely”, for instance. Furthermore, one other participant suggested that all members of the 48 hour accumulated precipitation product should represent diverse locations (as what was initially believed). In this sense, the emergency manager can gain a general sense of expected precipitation for locations that may be in close proximity as well as the potential impacts based on the vulnerability of known areas. A couple of other interviewees suggested incorporating a summary of the main ideas illustrated with each forecast product that pertains to precipitation. Other comments that related to more of the “housekeeping” side the products included clarifying and increasing the font size of the titles to emphasize the purpose of the products, spelling out station identifiers, and reducing the number of members. One participant even suggested making the 48 hour accumulated precipitation product more interactive by using something like a slide bar to change the precipitation measurement and date range of the product. Clarifying the title descriptions may be one of the most important suggestions made in this study, as at least one participant got confused with associating the precipitation color scheme with that commonly used to depict radar reflectivity. These observations support the fact that each human being perceives and processes information differently from others. It is a long-term goal of this study to develop forecast products that not only address the needs of hazardous weather information for decision makers, but also fit their learning techniques.

There were a couple of other interviewees that had called for other pieces of information to be included in the set of forecast products. One emergency manager would have liked if the probability product was county specific, especially relevant to fire burn areas in which case their time of response would be shorter. Another would have liked a wind vector map that showed speed and direction, as well as a lightning map. Furthermore, another participant would have also liked forecast information that pertains to their area, especially in terms of severe weather such as the probability for tornadoes in an effort to increase awareness in their communities. This was compared to being given a general forecast that is more relevant to their metropolitan neighbor. As it was acknowledged that the weather was greatly influenced by terrain interactions, this participant has observed how certain types of weather events that happen in the metro area do not happen in their jurisdiction. Given these observations, it may be of great benefit to this emergency manager, and others, to develop forecast products that focus on the present and future weather conditions at any given specified area (such as with the Short Range Ensemble Forecast plume).

Due to the length of the interviews, and other possible obligations that the interviewees needed to attend to, the next couple of questions were not presented to all participants. In any case, discussion will be given herein relevant to those that had the opportunity to share their thoughts. Given that the emergency managers were able to peruse the set of experimental forecast products and judge their value, they were asked to choose one or more of the products that they believed would be sufficient in their decision making process. Out of the five participants that responded to the question, four of them felt that all the products would be useful in their planning. Although one decision maker related solely to the simulated radar product as being adequate, further insight was given related to the field of emergency services in that better decisions were made with having more information. Such a statement carried through the other interviewees as well; there is no single ideal product to solely rely on for weather information and base decisions on. To these participants, all products were applicable in their own way, each telling the story of the weather in a unique perspective. Combining the diverse products would be useful in providing a well-rounded understanding of the forecast, the potential hazards, and making the informed decisions needed to prepare for what is forthcoming. As one emergency manager put it:

"You know, I, I don't think there is a perfect product out there for weather… That's why you call it forecasting because there's not a black and white definitive way to it. Some days you're in the ballpark and some days you're not. Um, so I think the more information you gather from different products, the between decisions you can make."

Although recognizing the usefulness of multiple weather products, at least one decision maker discussed the idea that humans as a whole tend to stay in their comfort zone and rely on what is known and familiar:

"… we're probably all guilty of relying on those things that we know and that we're comfortable with. Um, so we, we kind of set back into what we know and what's comfortable. And, and I would imagine that there's a lot of information out there… I could not tell you what it all is. I don't have time. I don't, I don't have time to research it…"

It is possible that the responsibilities and commitments of an emergency manager may serve as a hindrance or allow minimal time to learn of new weather products. This may also suggest that personal interactions or trust are important to them, as they are going to be reluctant in moving onto to something new and unfamiliar, a finding support by past social science research on emergency management decision making (e.g. Baumgart et al. 2008).

A follow-up question was presented related to which product the interviewees felt they would get the quickest, easiest, and/or most information from. Out of the four participants that were able to respond, at least one felt that they would get the most from the simulated radar product, finding the ability to see the potentials concerning the behavior of convection practical. One other emergency manager shared similar thoughts, but felt the product would not serve to provide other desired pieces of information. In turn, this decision maker was uncertain as to whether they could retrieve the most information out of any one product. The 48 hour accumulated precipitation product was favored by the third participant, as they clearly saw the timing and potential amount of precipitation within a certain time frame, regardless of not knowing the probabilities of each scenario. The last emergency manager felt that not one product dominated in providing the most information, as each product gave information to help realize the actions that needed to take place and the decisions that needed to be made. These observations show the fact that depending on what type of information the interviewee is concerned with most has an influence on which forecast product they feel effectively delivers that information.

4.3.3 Sources of information used to monitor storm behavior

Prior to evaluating the experimental forecast products, the participants were asked to describe the sources of information they would use to evaluate the threat for a warm season heavy rain event. It was of interest to compare these sources to what the emergency managers would use in the case that the hypothetical weather scenario presented transformed into reality and was currently active. There seems to be greater emphasis on using the combination of real time weather radar data and various sources of ground truth reports to be aware of, monitor, and respond to the current hazardous weather situation. Past studies have concluded that ground-truth reports of severe weather do play a critical role not only in the decision-making process of the NWS (McCarthy 2002), but also in the awareness and attention by EMs to warnings (Schumacher et al. 2010, Baumgart et al. 2008). Many of the decision makers described checking the observational radar frequently to show what is going on at the moment and potentially where the thunderstorms may go. One of these participants mentioned comparing observational radar to modeled reflectivity as a way to keep track of storm behavior and guide their plan of action in response to. It seems as though since weather radar have been around for so long and is a common tool used in operational settings, its familiarity and applications have paved the way for EMs to feel comfortable using it often in their jobs. Another interviewee found it helpful if given a storm projection in the midst of convective activity. This type of technology does exist but unfortunately is limited by the mountain terrain.

Many of the participants would also use local field reports from community weather spotters, live news broadcasts, and even social media products such as Twitter. These sources are able to communicate valuable observations to emergency managers regarding severe weather characteristics such as location, severity, dangers, and impacts. Such information can also be communicated through the personal accounts of civilians being directly impacted by a hazardous weather event. All the sources herein help to bring the weather situation at hand into perspective and generate an overall situational awareness, where decision makers can focus their attention on vulnerable populations and provide the necessary aid. Furthermore, a few interviewees described using stream and rain gauge observations to gain a sense of where the precipitation is falling, rainfall rates, what streams or creeks are experiencing the heaviest amounts to where flooding is a concern, as well as the status of retention and detention ponds. These local gauge systems are especially useful for one participant in knowing the susceptibility of burn areas, which are prone to flooding as the ground is unable to efficiently absorb rainfall.

Personal communication with the experts is an appreciated communication source, as a few of the emergency managers described contacting the NWS, contract meteorologists, UDFCD or Storm Water personnel to learn of the latest hazardous weather information through their perspectives. Notifications concerning flooding, transportation issues, or any other factors that may serve as an obstacle to societal functions would be relayed to these decision makers. As a side note, a few interviewees expressed interest in using the experimental forecast products during an active event. Although two of these participants just gave the impression that they would *generally* use the forecast products, the third participant stated that they would use the forecast products at a six-hour or twelve-hour interval, unless they were dealing with a dynamic, fast-moving storm or were notified of flood reports in neighboring jurisdictions.

4.3.4 Influence of forecast uncertainty, career, and personal experience

One of the main goals in this study was to learn how the interviewees' perception and understanding of forecast uncertainty would generally influence their decision making and/or plan of action following a hazardous weather event, such as the one presented in the hypothetical scenario. For a few of these emergency managers, the greater the likelihood of occurrence (as implied by higher probability of precipitation) serves as an advantage towards making better decisions based on the data. A greater probability in precipitation seems to yield greater confidence in the forecast provided to these decision makers that an event is likely to happen, where more attention is directed to the particular forecast and plans are made to better prepare the public for what is likely to happen. Some of these interviewees also recognized the difficulties in the science of forecasting, such as the hesitation in distributing the forecast with lack of convincing information or the accuracy associated with forecasting precipitation amounts. Ideally, better products that can relay better forecast information would have a positive influence on how societal functions operate. As stated by one participant:

"So, the accuracy of it is really important and forecasting is actually becoming much more of a science than throwing chicken bones in the air and see which way is it gonna land."

One emergency manager discussed how greater uncertainty in the forecast suggested to keep their resources close by and continue to monitoring the situation at hand. In addition, they also stated that in such a case, it may be worth the effort to focus on removing some of the uncertainty:

"Um, so I guess yeah you would keep your planning and your contingency planning in a tighter group the more uncertain it was. And maybe put more of an emphasis on trying to eliminate some of that uncertainty."

Another decision maker mentioned building extra contingency plans when dealing with a greater range in probability. It is thought that the "greater range in probability" meant that there was a lack of confidence, or greater uncertainty, in the weather forecast, such that more flexibility is needed to prepare for all possibilities.

A couple of other interviewees stated being deliberate with the lower forecasted probabilities as, despite the likelihood, the consequences of what could happen may outweigh. Although they would not necessarily take immediate action (such as activating the emergency operations center, EOC), they would still be concerned and prepare the appropriate personnel needed. As one of these participants stated: "… the higher the threat, the less the probability has to be for me to get concerned". An example of such a situation could be an ensemble forecast, where most of the members predict minor precipitation accumulation, while a few other members predict significant precipitation accumulation; it is a low probability event yet one that can place any individual at unease.

While all of the participants praised the relationship they have with the NWS, a few of them admitted relying more on other sources, such as contract meteorologists or the UDFCD, for their hazardous weather information. Practical reasons for this include: 1) would not want to take up time out of their active schedules, considering the limited number of forecasters in the office, 2) the challenge in setting up conference calls for local summer events, compared to winter events which typically impact a broader region and 3) generally have local meteorologists do the interaction (likely because they are the experts, there is expert to expert interaction). Meanwhile, all the other emergency managers have worked directly with the NWS to receive location-specific forecasts, and participate in weather briefings (via conference calls) during times of significant weather events (such as a snow storm or major flooding event). Furthermore, depending on the severity of the situation determines how much interaction there may be between NWS and the decision maker. At least for one interviewee, contacting neighboring emergency managers and learning their train of thoughts and plans is more of a common occurrence than contacting the NWS directly. It may be that the jurisdiction this particular interviewee is responsible for is not impacted by significant weather events often, compared to other counties in the state. Overall, the NWS is an invaluable resource to these decision makers, one of which they learn a great deal from.

Many of the interviewees in this study have served as an emergency manager for many years, enough such that they are likely to have observed changes regarding weather information and how they understand weather overall. Many of the participants have noticed great advancements in terms of the availability, quantity, quality, and versatility of weather forecasts. The relationships with the services that provide the weather information have also improved, particularly with the proactive character of the NWS. It is likely that the various informative sessions provided by the NWS has helped emergency managers become more aware of the weather patterns and what they translate to in the forecasts. These decisions makers, with experience, have a greater understanding of weather maps, how to identify certain interactions that may signal concerning weather, risks, and impacts. Overall, the combination of weather education and technological innovation has helped improved the communication and understanding of weather information. Furthermore, the diverse nature of Colorado's weather provides a dynamic environment that these individuals can learn and test their abilities in.

Towards the end of the interview, the interviewees were asked a couple of questions about how their work and personal experiences may have played a role in their decision making process during an event similar to the hypothetical weather scenario. In relation to the former, frequent exposure to diverse weather scenarios throughout the year on the job as an emergency manager has helped these participants build a historical collection of events. From this collection, they become familiar in a general sense with the synoptic and/or mesoscale patterns that are favorable for producing precipitation in their region, and what periods of the year are conducive for certain weather phenomena (e.g. monsoon, tornadoes). In particular, this recognition applies in the case of severe weather events, where the emergency managers have seen the destruction and casualty these incidents can inflict on society. Consequently, when the decision makers are faced with a weather scenario that has the conditions similar to what they have experienced from a memorable weather event in the past, they are aware of the possible outcomes and impacts. Using this information, they can better prepare their warning notifications and response procedures in their best effort to keep their communities aware of what is going on and protect life and property. Furthermore, the interviewees have also become familiar or comfortable with using and reading weather data. One participant used the example of learning to relate the "red spots" on the radar image heavy precipitation, and what certain amounts of rainfall translate to in terms of impacts on stream and street flooding. A couple of other participants described how the interactions with NWS, either through informal classes or during the active and recovery phases of a significant event, has educated them on weather charts and knowing when to take heed during a particular severe weather event. Overall, these emergency managers have become more educated and professionally versatile in how they manage hazardous weather events in their communities through the education received through self-learning and collaboration with other experts.

Many of the decision makers briefly recalled several significant weather events that have not only been a part of their work experience, but have also taken a toll on a personal level. One interviewee remembered being hit by the debris cloud from the tornado that hit Thornton, Colorado back in 1982. Recalling what the atmospheric conditions felt like that morning, and what resulted that afternoon, has taught this participant to be vigilant of your surroundings and be aware of early warning signs that may suggest the possibility of concerning weather. On a similar note, another emergency manager recalled a funnel cloud touching down near Denver, which had proven the misconception that tornadoes do not form in metropolitan areas. Such an event has taught this decision maker to never believe that the uncommon will never happen, and to always prepare for the worst-case scenario. Another interviewee recalled rescuing a relative from their home that was caught in a flash flood, and seeing similar events occur over time has taught this participant to personalize such incidents:

"… I think that's part of emergency management I guess, you know, you take this stuff in for real and you know, when you have those personal experiences on top of what you do for a living, um, you kind of understand that the consequences affect real people and real incidences, um, you know kind of thing…So there's been those events that have occurred over time that collectively, you know, when you see this, you kind of can then personalize and conceptualize what that means to somebody. Um, which is kind of why we do what we do."

The type of event that the emergency managers most often referred to was floods, particularly the Big Thompson flood that occurred on 31 July 1976. Many of these participants specifically remembered and were amazed by the stationary nature of the thunderstorm responsible for producing such heavy rainfall. A couple of the emergency managers were called to be on rescue teams for the event, where they were able to see the extent of damage and realize the power of nature. This historic event has personally made a lasting impression for at least one decision maker, as they reminisce of the flood when they observe a thunderstorm sitting over a particular location and propagating in place. This participant is aware that heavy precipitation associated with non-moving thunderstorms can cause flash flooding, especially in fresh burn areas where the soils are unable to absorb much of the rainfall. Knowing the devastation that has happened as a result of the Big Thompson flood has caused this participant to have greater concern and anxiety for stalled thunderstorms:

"To this day, um, I can't enjoy a good thunderstorm because of Big Thompson. When we get a forecast for a huge thunderstorm, now forget High Park, you know, which is a problem in of itself which has made me even more paranoid about rain events. But, ever since then, I mean it, it was, it left a lasting impression on me of what a big rain event that doesn't move can do. That was a, that shocked the hell out of everybody in this country."

It is likely that many of the other interviewees share similar feelings and use their experiences from the Big Thompson flood as a valuable reference for future events. At least one emergency manager was able to recall the flooding associated with the rain and hail storm that hit Colorado Springs on 6 June 2012, although no relation was made between the experimental forecast products and the actual event. Nevertheless, this decision maker was unaware that this particular storm was going to be motionless and precipitate heavily, learning that predicting the stationary-character of a storm is impossible. Experience with such events has taught many of these emergency managers the importance of their obligation to provide the public advanced warning information.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

5.1.1 Diagnosing the 6-7 June 2012 severe convective event

This study made use of a 24-member convection-allowing and convection-parameterized ensemble prediction system in order to assess their forecast skill of the 6-7 June 2012 severe convective event. In particular, a comparison between both ensemble systems was performed in order to address a variety of aspects in their performance: the source, timing, and location of convective initiation; the evolution of convection; the ability to adequately resolve observed mesoscale features; and the amount and spread of precipitation. The most important findings are addressed herein.

Despite the discrepancy in the timing, geographic location and evolution of convection, the convection-allowing ensemble forecasts represented the 6-7 June severe convective event as a whole reasonably well. Compared to the convection-parameterized ensemble forecasts, those from the convection-allowing ensemble illustrated greater detail in where to possibly expect convective initiation as well as the behavior of convection. A majority of the convection-allowing forecasts develop convection in the general vicinity of where the convergence boundary was observed. In addition, isolated convective cells were forecasted to impact within and near urbanized areas. These are the two primary forecast characteristics that the convection-parameterized ensemble was unable to realistically resolve. Given that the convection-allowing ensemble forecasts provided a better overview of the mesoscale convective activity, a more comprehensive analysis was given to study those particular forecast characteristics.

Overall, the 24-hour precipitation accumulation forecasts from the convection-allowing ensemble were able to sufficiently identify the approximate geographic area of where to expect precipitation, the range in amount, and where to expect the greatest precipitation. However, the forecasts illustrated several differences in the spatial and quantitative characteristics of precipitation, some of which were correlated to how the ensemble members forecasted the radar reflectivity. A majority of the 24-hour precipitation forecasts showed an eastward displacement of precipitation, which was consistent with the eastward bias in convective initiation. Also, many of the ensemble members displaced, missed, or underestimated precipitation maxima compared to the analyses.

Key differences were identified within the convection-allowing ensemble members to illustrate the important mesoscale processes needed to adequately resolve the convection. While the "good" ensemble members were able to roughly capture the convergence boundary and place it in the more or less geographic area, the "poor" ensemble members placed the boundary well south and east compared to what was observed. Further analysis was dedicated into whether the predicted boundary was indeed its own feature, or was it a manifestation of the cold front. Amazingly, the "good" ensemble members altogether illustrated the cold front bounded to the border of Wyoming, Nebraska, and Colorado while the "poor" ensemble members depicted the cold front too far south.

Convection-allowing ensemble member #15 adequately represented the backbuilding convection associated with the initial boundary convection, as well as with the Denver convective cell. This was attributed to the simulated outflow boundaries associated with both features. As for the Colorado Springs cell, there was no strong indication of an outflow boundary near its vicinity. Although convection-parameterized member #6 did an okay job at simulating the convective activity along the convergence boundary and near the urbanized areas, it did not provide as clear of a depiction of backbuilding convection in either case. These comparisons illustrate the significance of the outflow boundaries in the development of backbuilding convection near the convergence boundary and for at least the Denver convective cell. As for the Colorado Springs convective cell, warm, moist air advection from the southeast continuously fed into the area, likely producing upslope flow over the Front Range and feeding into the convection.

5.1.2 Understanding of hazardous weather information by emergency managers

A total of 9 Front Range emergency managers (EMs) were interviewed to research how they understood hazardous weather information, and how their perception of forecast uncertainty would influence their decision making following a heavy rain event. Many of the participants learned about the typical summer weather patterns in Colorado through situational awareness. Furthermore, their experiences with major weather events helped to guide their emergency preparation and response. These decision makers also highly valued their relationship with the National Weather Service to retrieve and improve their understanding of current weather situations and to ask questions concerning forecast uncertainties.

Most EMs perceived forecast uncertainty in terms of the probability and intensity of the forecasted precipitation, as well as its spatial and temporal variability. The greater the likelihood of occurrence showed greater confidence in the forecast that an event was likely to happen. However, some of these EMs also recognized the difficulties in the science of forecasting, such as the hesitation in distributing the forecast with lack of convincing information or the accuracy associated with forecasting precipitation amounts. A couple of other EMs stated being deliberate with the lower forecasted probabilities as, despite the likelihood, the consequences of what could happen may outweigh.

Five probabilistic forecast products were generated from the convection-allowing ensemble output to generate a hypothetical warm season heavy rain event scenario. Responses varied among the EMs in which products they found most practical, least useful, or too overwhelming. The time series product was the least liked, as many found it consisting of too much detail, obscure in context, and beyond the scope of their understanding. Products that provided a quick overview of the weather with simple descriptions were more favored. An example would be the probabilistic precipitation forecast product. The quick visual of the forecast and its simplicity in presenting information regarding where precipitation may fall and estimated amounts were among the modest comments received. The 24-member 6-hour accumulated precipitation product was favored by most EMs as a useful way to learn what areas may receive precipitation and also how much. Most EMs also felt that there was a high probability for flooding, as illustrated by the degree of forecasted precipitation intensity.

It is interesting that at least one decision maker made the comment that humans, as a whole, tend to stay in their comfort zone and rely on what is known and familiar. For example, all of the participants were most familiar and comfortable with the NWS 7-day forecast out of all products. It is possible that the responsibilities and commitments of an emergency manager may serve as a hindrance or allow minimal time for them to learn new weather products.

Frequent exposure to diverse weather scenarios throughout the year on the job as an emergency manager has helped these participants build a historical collection of events. From this collection, they become familiar with the synoptic or mesoscale patterns that are favorable for producing precipitation in their region, and what periods of the year are conducive for certain weather phenomena. In that sense, when the EMs are faced with a weather scenario that was similar to one in the past, they are already aware of the possible outcomes and impacts. Using this information, they can better prepare their warning notifications and response procedures in their best effort to keep their communities safe. Overall, this study hopes to address the needs of decision-makers in relation to improving hazardous weather communication, understanding, and response. The long-term goal of this research is to develop and add reliable probabilistic forecast products to the “toolbox” of decision-makers to help them better assess hazardous weather information and improve warning notifications and response.

5.2 Future Work

During the second week of September 2013, portions of northern Colorado experienced one of the worst heavy rainfall events in its history that led to great devastation and loss of life. Persistent moist, upslope flow was the primary cause of widespread rainfall, as an upper level low remained over the desert southwest and fed subtropical moisture north across Colorado. Flooding initiated in the foothills and mountains, later moving downstream throughout the week. Boulder, Colorado was one of the hardest hit areas, receiving over 18.00 inches of precipitation. Such a high-impact precipitation event provides several opportunities for future work using the ideas and methods presented in this study. The comparison of ensemble forecast systems (convection-allowing versus convection-parameterized) can be applied to this weather event to gain a better perspective of the forecast certainties and uncertainties, as well as resolving the complex processes that governed the nightly rainfall.

Additionally, given the magnitude of its impact, this event would provide great insight into how emergency managers actually perceived and responded to the weather information concerning the flood risks. It would be of interest to compare such findings to those concluded from the hypothetical weather scenario considered in this research work. Such comparisons could produce a more realistic example of how they operate during an actual crisis as opposed to a hypothetical one. Through this process, effort can be dedicate towards refining the process regarding the communication of weather information to emergency managers.

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