15A.2 Some Challenges And Successes Associated with Using Storm-Scale Modeling at a NWS Forecast Office

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1. INTRODUCTION

At the turn of the century Numerical Weather Prediction (NWP) had made significant advances in vertical and horizontal resolution. Local modeling efforts were becoming widespread at National Weather Service (NWS) field offices and for the first time computing power allowed modelers to run at higher resolutions capable of resolving moist convective processes. Researchers began producing successful results when explicit convection allowing models were run at resolutions below 8-km (Fowle, M.A., and P.J. Roebber, 2003), and other scientist studied the benefits of increasing the resolution (Mass et. al., 2002, and Kain et. al., 2008). It was demonstrated that high resolution brought significant improvement in complex terrain and storm-scale predictions. In addition, despite spatial or temporally misplaced convection, which can led to large variability in grid point verification, the results proved to bring attention to potential mesoscale events and improved conceptual model information to the forecasters.

The research community continued to experiment with high-resolution models down to cloud-scale (Bryan, 2003) and during each Hazardous Testbed season with a focus on severe convective weather (Kain et. al, 2005 and 2006, Weiss et. al., 2007). The results were encouraging but recommendation for sensitivity studies and ensemble modeling led to numerous studies (Etherton, B., and P. Santos, 2008, Case et. al., 2008, Schwartz et. al., 2010). The studies resulted in significant improvement to storm-scale modeling and demonstrated uses for severe weather forecasting (Coniglio, 2008), but there infusion into Weather Forecast Office (WFO) operational forecasting has been slow to occur. Since the National Center for Environmental Prediction (NCEP) has been producing operational high resolution models below 5 km there have been fewer studies demonstrating WFO operational applications to bridge the gap discussed by Roebber et. al. (2004). In 2007, Hultquist documented uses of storm-scale WRF modeling on bow echo prediction, and Tardy (2009) demonstrated applications for convective initiation in complex terrain. Researchers have also produced published guidance for convective parameters (Sobash et. al., 2008). Most recently, the COMET program [available online at: www.meted.ucar.edu] published the first significant national training, titled "Effective Use of High-Resolution Models", for the operational forecasters.

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2. MODELS AND PARAMETERS

Several versions of high-resolution convection-allowing NWP are available online and valid out to 48-h. This study examined the following: 4-km National Severe Storms Laboratory-WRF which uses the Advanced Research WRF (ARW – Skamarock et al., 2005) model to produce a daily forecast, NCEP 4-km high resolution window versions of both the ARW and Non-Hydrostatic Mesoscale Model (NMM), a Storm Prediction Center (SPC) daily NMM run provided by NCEP (Weiss, 2008), and the University of Oklahoma's Center for Analysis and Prediction of Storms (CAPS) 1-km ARW model (Xue et. al., 2009). At the WFO level similar versions of the WRF model can be run using the, the Environmental Modeling System (EMS) model [online at http://strc.comet.ucar.edu].

A simple approach for the operational use of storm-scale modeling was used in this study, similar to Koch et. al. (2005), which limited parameters to Quantitative Precipitation Forecasts (QPF) and simulated reflectivity. Recent studies have used other parameters for severe weather prediction such as updraft helicity (Sobash et. al., 2008) and ensembling methods (Stratman et. al., 2009). It will be demonstrated that the use of QPF and model simulated reflectivity output can greatly enhance forecasters in the anticipation of high impact events, down to the storm-scale level, and greatly increase confidence and abilities to provide enhanced decision support services. This paper will use several examples to demonstrate the applications and also discuss limitations with the use of high-resolution datasets.

3. DECISION SUPPORT SERVICES

The incorporation of storm-scale modeling into operation weather forecasting was the goal of most initial research and improving NWP verification is critical. However, advancements in NWP have now made it imperative to depict this output in deterministic gridded forecasts and probabilistic information. Since the users of the weather forecasts have specific requirements and thresholds dependent on this information, the NWS is more than ever in the position to provide interpretive services for a variety of decision makers. Therefore, the purpose of this paper is to demonstrate how storm-scale modeling can used as a tool to enhance this critical information.

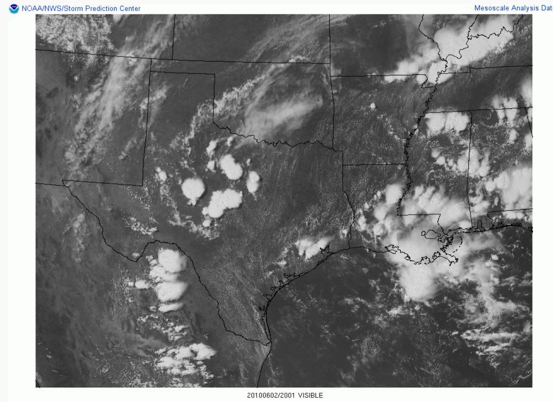

Fig. 1. GOES visible image at 2000 UTC 2 June 2010.

4. MODEL DATA AND EXAMPLES

The use of storm-scale NWP has proven to be challenging in conditions where atmospheric forcing is weak and convection is largely driven by micro-scale boundaries. However, Clark et. al. (2009) showed that 4-km QPF skill excels compared to courser resolution for deterministic and ensemble runs. The first example appeared to have similar challenges but further investigation revealed a near perfect depiction of high resolution modeling and opportunity for improved decision support services.

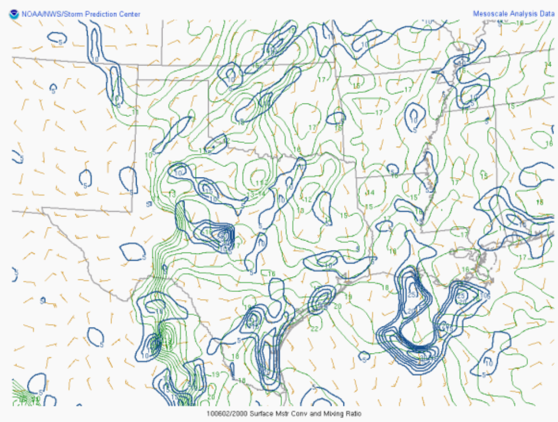

Fig. 2. SPC mesocale analysis of surface moisture convergence and mixing ratio. The typical sea breeze convergence is shown along the Texas coast and in other areas across central Texas.

4.1 Quasi-Linear Convective Systems

During the afternoon hours on 2 June 2010, forecasters were challenged with a conditionally unstable environment but minimal convection across South Texas. Geostationary Environmental Satellite (GOES) imagery depicted areas of deep moist convection in Central Texas and along the higher terrain of the Sierra Madre in Mexico (Fig. 1). Further analysis of mesoscale data from the Storm Prediction Center (SPC) indicated strong surface moisture convergence along the South Texas coast associated with an inland penetrating sea breeze (Fig. 2). However, this forcing mechanism alone has proven to be insufficient for parcels to reach their level of free convection (LFC) in strongly capped atmospheric environments. Figure 3 revealed large values of mixed-layer Convective Available Potential Energy (MLCAPE) across all of Texas and limited convective inhibition (CIN). This brief analysis may suggest weak forcing and locally driven convection only.

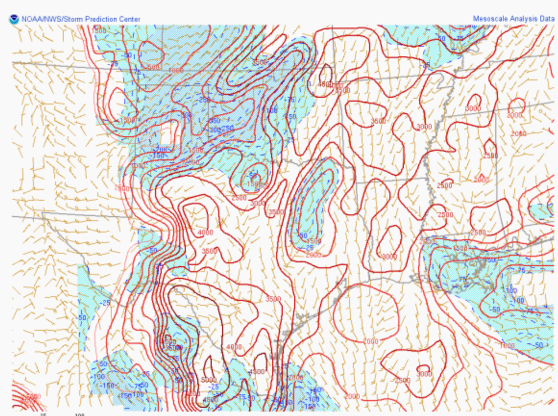

Fig. 3. SPC mesoscale analysis of mixed layer CAPE (jkg^{-1}) and mixed layer convective inhibition at 2000 UTC 2 June.

An upper level analysis on 2 June, demonstrated considerably strong synoptic-scale forcing and moderate wind flow considering the time of year (Fig. 4). The past several years SPC has offered combined parameter indices and for this case we examined the derecho composite. This parameter is based on a data set of 113 derecho events

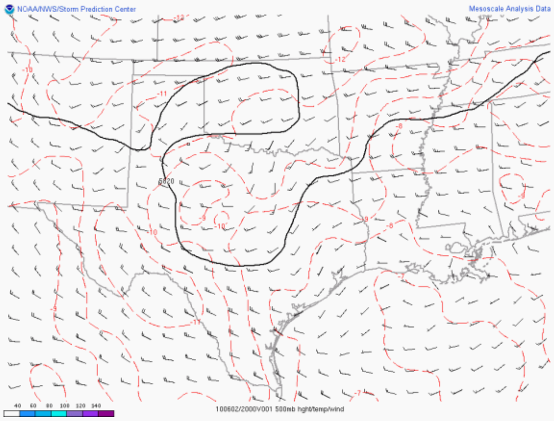

Fig. 4. SPC mesoscale analysis for 500-mb geopotential height, temperature and wind at 2000 UTC 2 June.

compiled by Evans and Doswell (2001) developed to identify favorable cold pool environments wind events using the following: Cold pool production (Downdraft CAPE), most unstable parcel CAPE near a gust front (MUCAPE), organization potential for convection considering 0-6 km shear, and sufficient flow within the ambient environment to favor development downstream using 0-6 km mean wind. Figure 5 clearly highlights South Texas to be in a favorable region, however high CAPE values are common in this climate and may be misleading.

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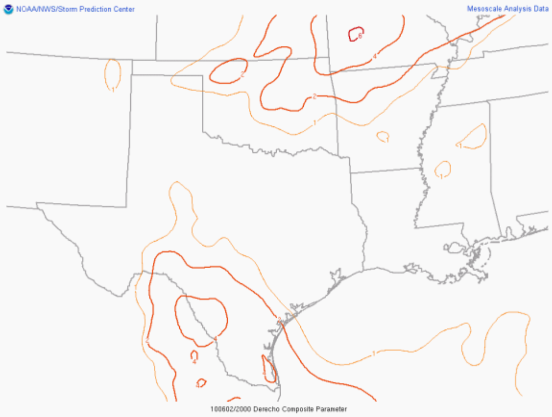

Fig. 5. SPC mesocale analysis for derecho composite at 2000 UTC 2 June.

The next step in the process is to evaluate NWP and successive model runs if possible. Model runs from 0600 UTC 2 June, almost 18 hours prior to the time period of concern, highlighted areas of heavy precipitation in Southeast and deep South Texas (Fig. 6 and 7), However, QPF placement (see Fig. 6 and 7), and to an extent the timing in reflectivity forecasts (Fig. 8), varied greatly in Southeast Texas but indicated great similarities between the NMM and ARW runs across South Texas. Therefore, the question at this point is could this information add value or confidence? For this case, this can be

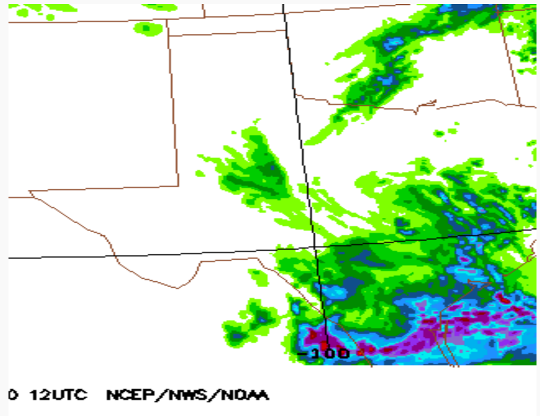

Fig. 6. NCEP-ARW 0600 UTC 2 June 12-h QPF valid at 1200 UTC 3 June 2010.

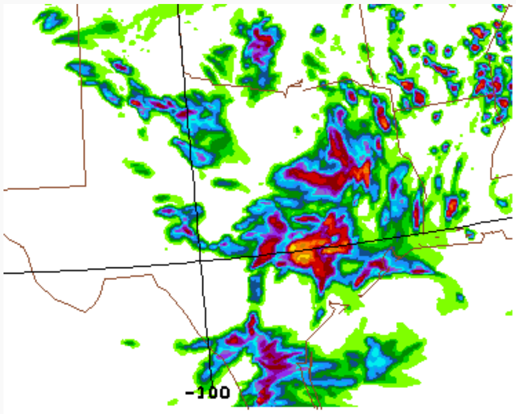

Fig. 7. NCEP-NMM 0600 UTC 2 June 12-h QPF valid at 1200 UTC 3 June.

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answered using the latest high-resolution modeling.

The CAPS model used in this paper is only available during the Hazardous Weather Testbed (HWT), but it proved to provide substantial value to the forecast process as depicted in Figure 9. It is understood that one deterministic model would need to be supplemented by ensembling members to develop the best confidence, the use of the CAPS model in this case proved to provide the forecaster with the conceptual model and increased confidence level to provide superior digital forecasts, advanced decision support and possibly better operational warning approaches. In this case, the improvement over current 4-km WRF versions for storm-scale applications may also suggest the need for 1 to 2-km grid spacing and higher temporal output, as well as better boundary layer assimilation techniques. Radar imagery in Figure 10 demonstrated the success of the model and a major high impact event that unfolded.

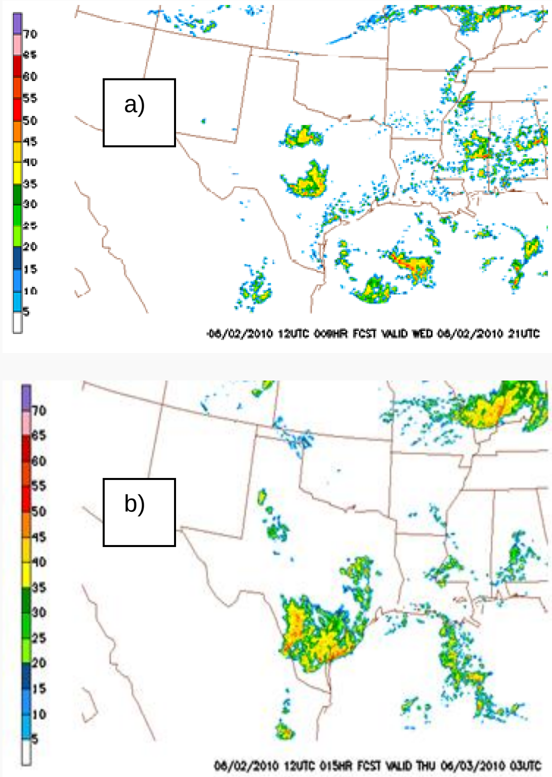


Fig. 8. 1200 UTC 2 June NCEP-ARW simulated reflectivity at 2100 UTC 2 June (a) and 0300 UTC 3 June (b).

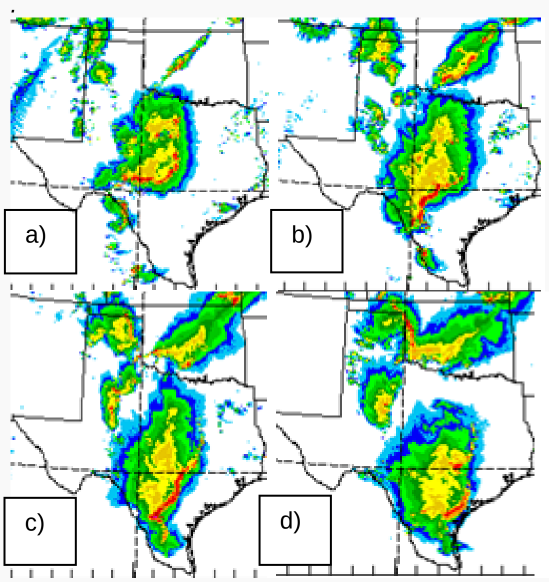


Fig. 9. 4-panel depicts the 1200 UTC 2 June 2010 CAPS simulated reflectivity. Time increases from a to d approximately 2200 to 0300 UTC.

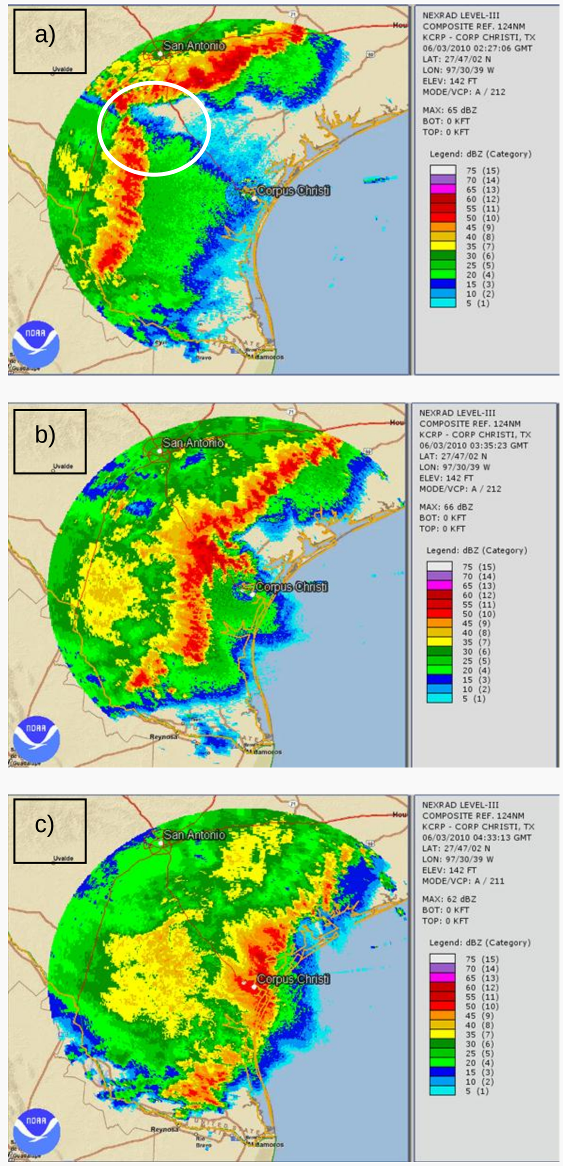


Fig.10. KCRP composite reflectivity at 0227 UTC (a), 0335 UTC (b), and 0433 UTC (c) 3 June 2010.

During the evening hours from 0000 to 0600 UTC, two mesoscale convective complexes (MCC) developed. The first MCC organized from the Sierra Madre in Mexico and moved east across South Texas. A second MCC rapidly formed in Central Texas and tracked southeast merging with the other complex near 0400 UTC. After the merger, widespread severe winds, estimated up to 50 ms^{-1} on WSR-88D (Fig. 11), and isolated tornadoes as strong as EF2 occurred across the Coastal Bend of South Texas. Damage was from severe wind was extensive with hundreds of trees down, numerous recreational vehicles overturned, power outages, and severe damage to roofs and carports. Figure 12 depicted the magnitude of the thunderstorms.

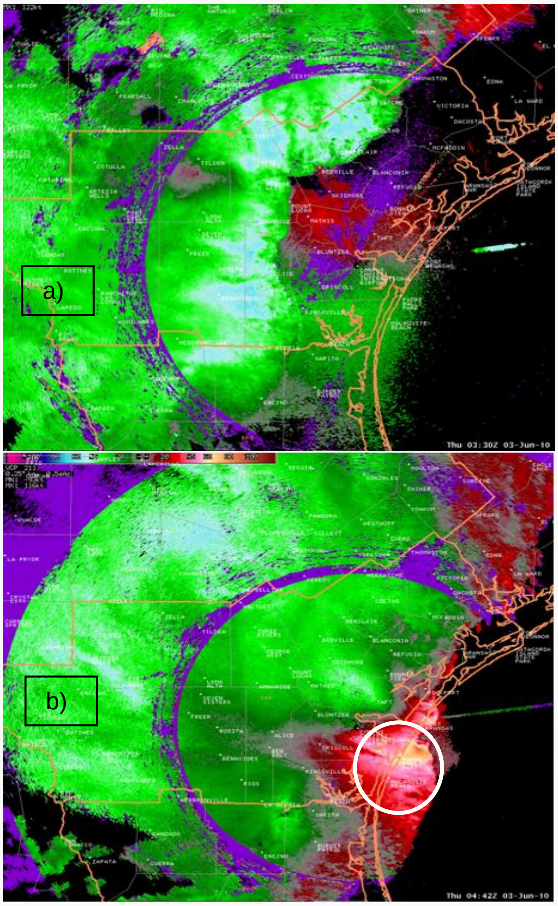


Fig. 11. KCRP base velocity at 0330 (a) and 0442 UTC (b) 3 June 2010. Outbound velocity slightly exceeded 50 ms $^{-1}$(circled).

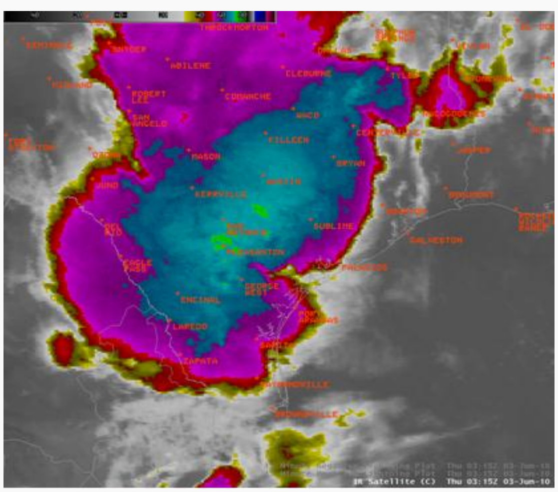


Fig. 12. 0315 UTC 3 June 2010 GOES infrared image.

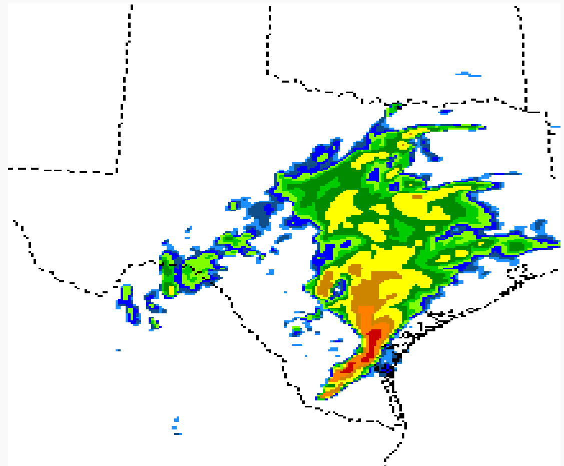


Fig. 13. Model 1-km AGL reflectivity at 0900 UTC 9 January 2011 from the 0000 UTC 9 January SPC – NMM run.

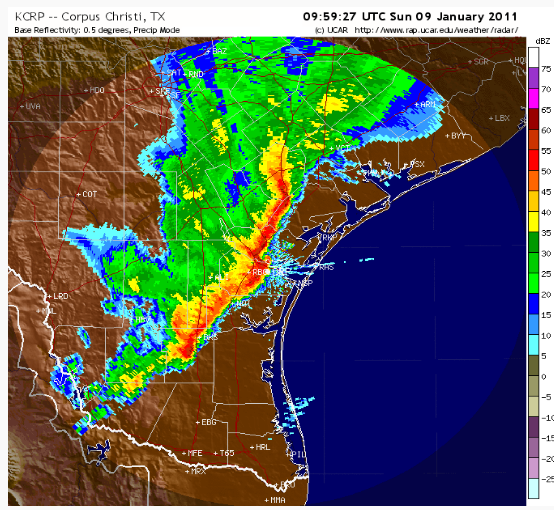


Fig. 14. KCRP base reflectivity at 0959 UTC 9 January 2011.

The success and application of the current high-resolution modeling is not limited to research models such as the 1-km CAPS. Several months later another squall line of nocturnal severe thunderstorms moved across the same region of South Texas. The model depiction of storm type, intensity, timing and location by a 4-km NMM version were remarkable as shown in Figures 13 and 14. These two high impact events support the urgency to implement such modeling, and educate operational forecasters on their applications and decisions support potential. We would like to mention that each case will not have similar success, but numerous other events supported the use of high-resolution deterministic modeling.

4.2 Tropical Cyclone outer bands

In addition to storm-scale modeling we wanted to review high-resolution modeling applications with tropical cyclone rain bands, The rain bands can be rather narrow and concentrated, thus it was anticipated that fine horizontal resolutions may greatly improve reflectivity forecasts. The NWP demonstrated considerable success for Tropical Storm Hermine which made landfall in deep South Texas (Fig. 15). Model simulated reflectivity improved short-term forecasts prior to landfall and the eyewall heavy rainfall.

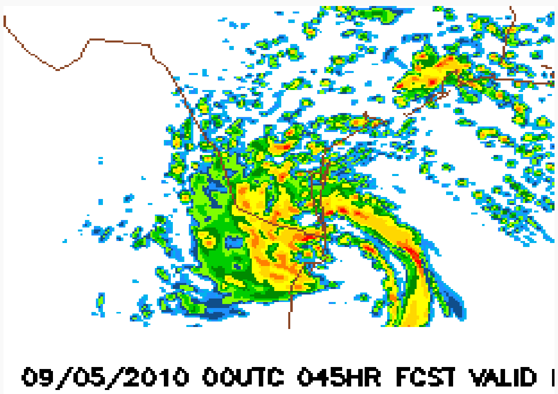


Fig. 15. 0000 UTC 5 September 2010 4-km WRF depicted outer bands of Tropical Storm Hermine impacting the Texas Coast.

4.3 Excessive Precipitation

A major challenge facing forecasters is the anticipation of excessive rainfall and resultant flooding. The use of high-resolution QPF was valuable to alert forecasters for extreme precipitation. During the period December 20-22, 2010 widespread heavy rainfall resulted in flash and river flooding, along with landslides, across much of Southwest California. Human advances in orographic precipitation forecasts have been demonstrated in the past, but an advantage to NWP is that during strongly forced systems and high moisture levels the models may also suggest heavy precipitation across less topographic enhanced regions. This was the case across Southwest California as depicted in Figures 16 and 17 when NWP predicted widespread heavy rainfall along the coast and interior valleys. The QPF was generally verified by radar analyses that indicated 4 to 6-in rainfall and significantly higher across upslope areas.

On 19 September 2010, widespread 6 to 10-in rainfall occurred in the greater Corpus Christi, Texas area. The rainfall was partially associated

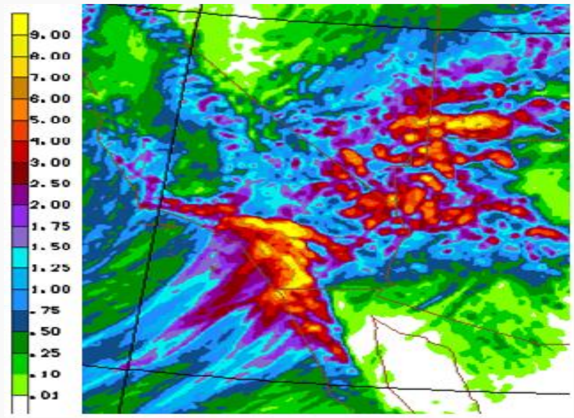


Fig. 16. NCEP 4-km NMM from 0600 UTC 20 December 2010 48-h run total precipitation.

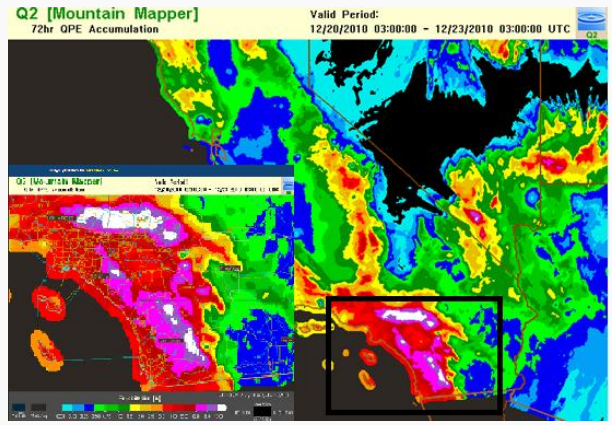


Fig. 17. Quantitative Precipitation Estimate from Q2 analysis for 72-h period ending 0300 UTC 23 December 2010.

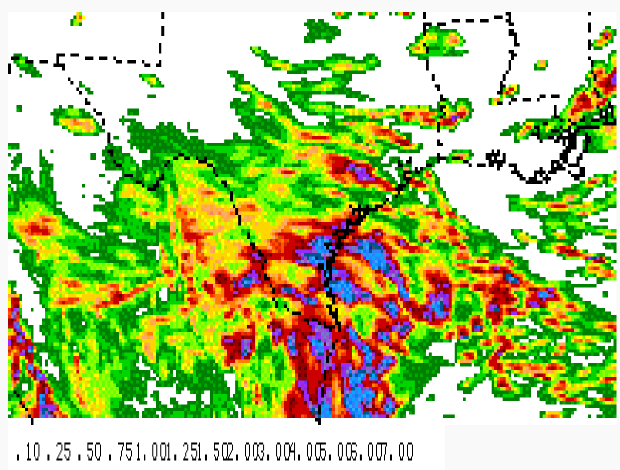
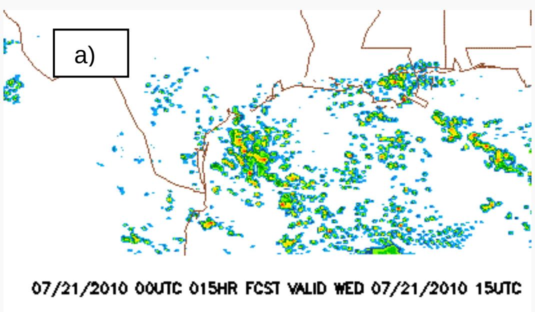


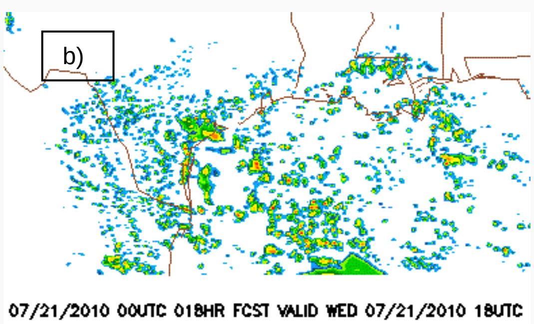
Fig.18. NCEP WRF-NMM 4-km 0000 UTC 19 September 2010 total accumulation valid at 36-h. Amounts exceeded 7-in across the Coastal Bend around Corpus Christi.

deep tropical moisture well north of Hurricane Karl. The resultant runoff produced record high levels on Oso Creek which drains through the city of Corpus Christi and a flash flood fatality. High-resolution model forecasts correctly identified this region as having the potential for excessive rainfall (Fig 18). These forecasts used with other data could be used to alert decision makers of an extreme event in a general location allowing for better preparation.

4.4 Sea breeze and coastal convergence

At the WFO level, mesoscale interaction often result in the least confidence in forecasts but greater potential impacts. Sea breeze circulation and coastal wind speed convergence play important roles toward enhancing and suppressing convection along the Texas Coast. An example, that demonstrated both of these processes occurred 21 July 2010. High-resolution modeling depicted accurate simulated reflectivity between 1500 and 2100 UTC. Warm unstable Gulf of Mexico waters and the leading of edge of a sea breeze supported enhanced convection, however subsidence in the wake of a diurnal sea breeze resulted in widespread suppression (Fig. 19).





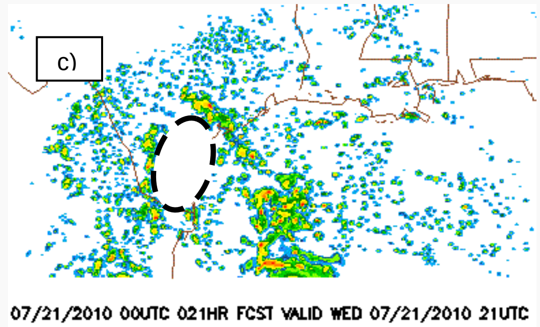


Fig. 19. NCEP ARW 0000 UTC 21 July 2010 simulated reflectivity forecast valid at 1500 (a), 1800 (b), and 2100 UTC (c) 21 July. Subsidence in the wake of the sea breeze noted in dashed circle.

In Figure 20, a similar coastal convergence in South Texas formed and produced localized flooding and funnel clouds on 15 September 2010. Model simulated reflectivity provided information on timing and general orientation of the precipitation beyond radar extrapolation and a conceptual model that forecasters could portrait in gridded deterministic and probabilistic forecasts.

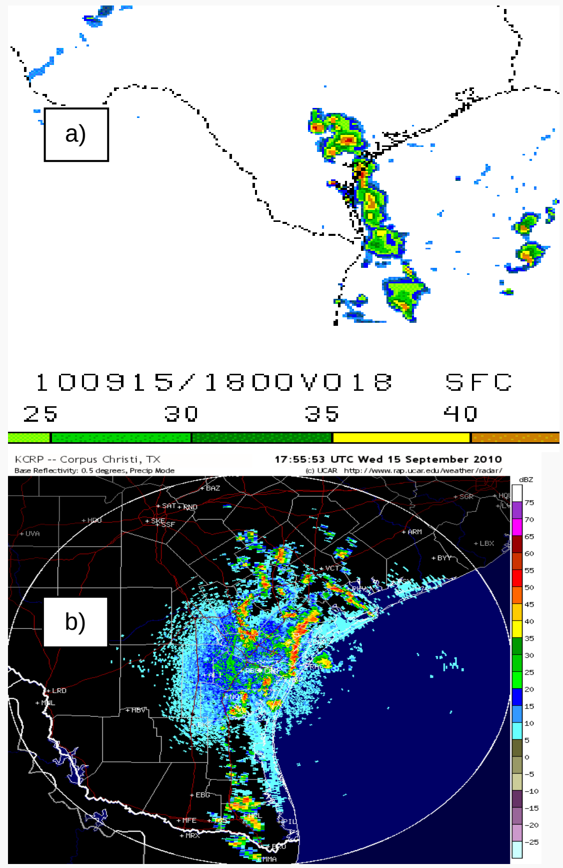


Fig. 20. NCEP NMM 0000 UTC 15 September 2010 run valid at 1800 UTC (a), compared to KCRP base reflectivity valid at 1756 UTC (b).

4.5 Elevated and surface-based convection with upper low

The purpose of this paper was to demonstrate some of the key advantages and applications of high resolution models. The final case was used to depict one advantage of using these models, versus traditional NWP, in synoptic scale patterns that may produce small scale surface or elevated-based convection (Fig. 21). This particular challenge is occasionally found in southwest California when an upper-level low interacts with sub-tropical moisture, Initially one challenge presented to forecasters is the details in these types of weather patterns can be noisy and difficult to apply. The skilled use of simulated reflectivity can greatly improve short-term forecasting and increase confidence levels (Fig. 22).

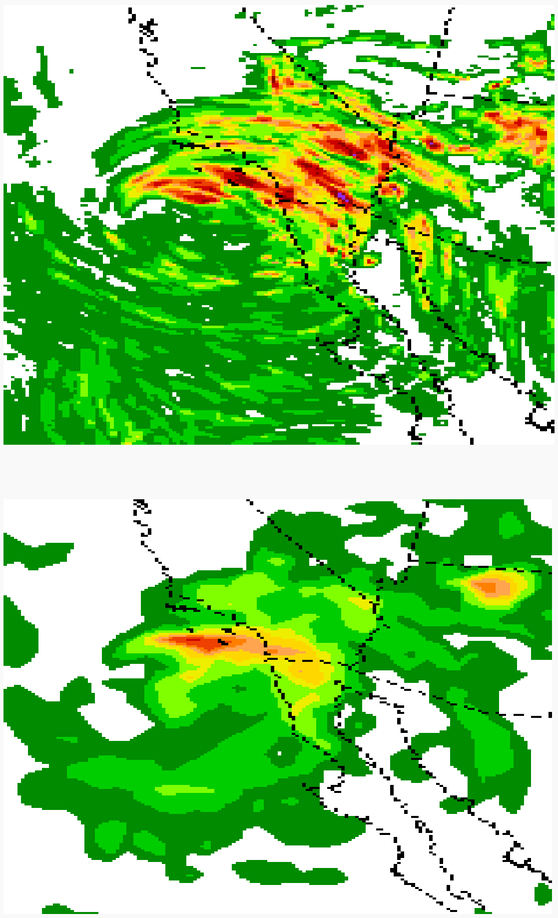


Fig. 21. 0000 UTC 19 October 2010 runs of the 4-km SPC-NMM (top) and 12-km NAM (bottom) with 36-h total precipitation.

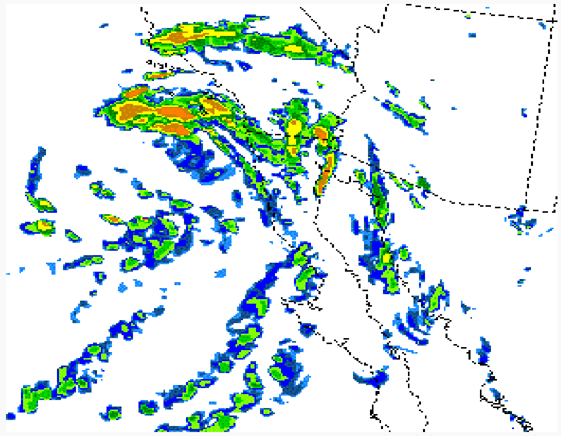


Fig. 22. Maximum reflectivity at 1-km AGL from the NSSL WRF-ARW 0000 UTC October 19, 2010 run valid at 1500 UTC 19 October. Surface-based and elevated thunderstorms impacted southern California.

5. LIMITATIONS

Weisman et. al. (2008) documented some of the key limitations to storm-scale modeling including timing and location, as well as issues with model assimilation techniques with sensitivity to initial conditions and planetary boundary layer interactions. In this paper a common limitation in many of the cases was the rapidly decreasing convective representation beyond 36-h. In some of the events, where forcing was the weakest, the reliability of the model dropped to 12 to 24 hours (Fig. 23).

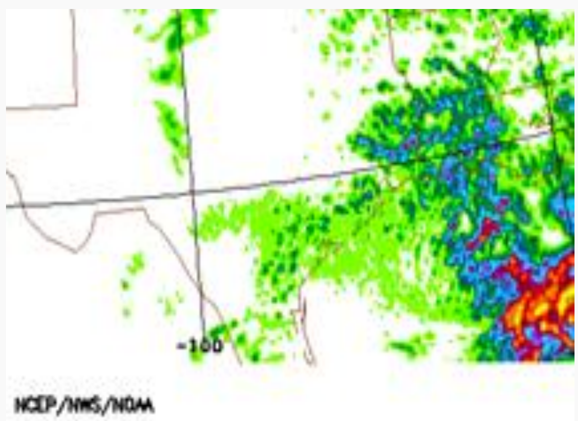


Fig. 23. The 0600 UTC 1 June 2010 NCEP WRF-ARW run depicted 24-h QPF valid at 0600 UTC 3 June. Minimal moist convection was predicted and appeared to be confined to the sea breeze.

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6. CONCLUSIONS

This study demonstrated the use of a high-resolution NWP for applications involving storm-scale modeling and short-term weather forecasting. Model output parameters used were simulated reflectivity and QPF which demonstrated considerable skill for enhancing conceptual models and confidence levels in high impact events, as well as generally anticipating convection and extreme precipitation. The overall benefit for the use of this modeling is to improve digital forecast information and enhance support for decision makers.

Understanding model limitations are part of the forecast process and forecasters need to be aware of temporal and spatial errors that can be magnified with high-resolution modeling. The use of ensemble members to provide probabilistic information and confidence levels should be beneficial to the process. Therefore, sufficient training and experience with storm-scale modeling should greatly improve current weather and hazard information we provide today. In addition, forecasters are in a greater position to provide interpretive services for this information.

Acknowledgements

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