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Project Title: The Potential Operational Impact of Missing Mexican Radiosonde Observations on Situational Awareness and Severe Weather Forecasts

Partners or Cooperative Project: NA06NWS4670013 UCAR Award No.: S09-~~75790~~ 81071

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SECTION 1: SUMMARY OF PROJECT OBJECTIVES

1.1 UA

This COMT Partners Project was conceived to take advantage of emerging research findings from a then-ongoing COMET Cooperative Project (S07-66811) involving UA, the SPC, and NWS/WFO-TUS. One motivation for the COMET Partners Project proposal was the opportunity it provided to investigate the potential impact of the recent (2006-2009) degradation of the Mexican radiosonde network on numerical model (NCEP/GFS) forecasts of synoptic-scale weather systems (in particular, upper-level closed cold cyclones) capable of triggering organized deep convection during the warm season summer monsoon over the Southwest. Results from our COMET Cooperative Project provided an additional motivation for this COMET Partners Project. They indicated that westward- and eastward-moving upper-level potential vorticity disturbances (PVDs) that reached Arizona from the Gulf of Mexico and eastern Pacific, respectively, played an important role in creating favorable vertical wind-shear profiles for the formation of convection over the higher terrain of Arizona that could subsequently organize into MCSs capable of producing severe weather in the populated lowlands of southern Arizona

The question arose as to whether the failure of the GFS model to resolve some of the observed severe weather-producing upper-level PVDs could be related to the degradation of the Mexican radiosonde network during 2006-2009. For example, the absence of Mexican upper air observations during July 2008 resulted in large upper air data voids through key parts of the monsoon region. The resulting greater analysis uncertainty limited the ability of human forecasters to diagnose the state of the observed atmosphere and to identify potential PVDs. At issue was whether the greater analysis uncertainty would translate into greater PVD model forecast uncertainty. This issue was addressed by means of a series of numerical experiments made by Tim Melino that employed the Weather Research and Forecasting (WRF) model v3.1.1, with the Advanced Research WRF (ARW) and Nonhydrostatic Mesoscale Model (NMM) dynamic core packages. The main focus has been on the ARW core because it allows a higher level of modification than that of the NMM core. The model was run on several representative severe weather-producing PVD case studies discussed in the Melino (2010) and Sukup (2010) M.S. thesis.

SECTION 2: PROJECT ACCOMPLISHMENTS AND FINDINGS

2.1 UA

Melino (2010) conducted two types of Weather Research and Forecasting (WRF) modeling studies. The first type was targeted at tracking the formation of subsynoptic-scale PVDs by the PV fracture process and their subsequent evolution to help address the question of whether these PV features could be forecast correctly in the absence of Mexican radiosonde data. These simulations employed a single grid with 25-km horizontal grid spacing and the forecasts were run to 84 h. The National Center for Atmospheric Research (NCAR) advanced research WRF (ARW) dynamic core (Skamarock et al. 2005) was used in this study. The WRF model was run using a single domain, which contains the CONUS southward to South America and also much of Canada. The resolution of these model runs were limited to 25-km due to the computational constraints associated with a relatively long range forecast on such a large domain. Forecasts in this experiment were run to 84-h ending on the day of the convective event and providing hourly output. The WRF model was initialized using the 1° NCEP GFS initialization files. Although NCEP 0.5° GFS files were available for several of the cases, they were not used to avoid potential uncertainties from mixed resolution analyses. All model initialization files used were available from the NOMADS archive (http://nomads.ncdc.noaa.gov).The WRF model was run using the Betts-Miller-Janic (BMJ) convective parameterization along with the WRF double moment 6 class scheme (WDM6) (Lim and Hong 2010) for microphysics, and were subject to 6 hourly lateral boundary updates from the GFS. WRF model-forecast PV was verified subjectively against observational analyses was using the 1° NCEP-GFS gridded datasets. A comparison between the WRF model configurations can be seen in Table 2 (as numbered in Melino 2010).

The second type of WRF-ARW study was targeted at the modeling of individual convective events. The purpose of the convective modeling study was to determine the ability of the WRF-ARW model to accurately forecast convective events and MCS development, and to obtain useable high-resolution model "data" (temporal and spatial) for further analysis. The domain for this experiment was different than that of the previous example and was configured using a two-way nested grid, an outer 12-km domain centered on the Southwest and an inner 4-km nest centered on Arizona (see Melino 2010 for details). After some initial experimentation, the model was configured with WDM6 microphysics (Lim and Hong 2010), RUC Land-Surface, Mellor-Yamada-Janjic (ETA) TKE scheme, and Kain-Fritsch (KF) (Kain and Fritsch 1993) convective parameterization in the outer 12-km domain only. In the inner 4-km domain, forecast convection was calculated explicitly. The WRF model was initialized in each case using the 12-km North American Mesoscale model (NAM) with lateral boundary updates processed every 6-h. The model was initialized at 1200 UTC the day of a severe weather outbreak and run to 1200 UTC the following day. Verification of these runs was done subjectively using satellite, radar, surface, and upper-air data, along with various gridded data sources.

Table 2: Key WRF Model setup parameters for both the PV tracking and severe weather modeling studies

Key Model Parameters	PV Tracking Study	Severe Weather Modeling Study
Microphysics	WRF Double Moment, 6 Class Scheme	WRF Double Moment, 6 Class Scheme
Shortwave	rrtm Scheme	rrtm scheme
Longwave	Dudhia Scheme	Dudhia Scheme
Surface-Layer	Monin-Obukhov (Janjic Eta) Scheme	Monin-Obukhov (Janjic Eta) Scheme
Land-Surface	RUC Land-Surface Model	RUC Land-Surface Model
Boundary-Layer	Mellor-Yamada-Janjic (Eta) TKE Scheme	Mellor-Yamada-Janjic (Eta) TKE Scheme
Cumulus Option	Betts-Miller-Janjic Scheme	Kain-Fritsch (new Eta) Scheme

Two case studies are documented here to show the "flavor" of the numerical simulations and the ability of the 25-km WRF model to forecast the PV fracture process and resulting formation of a PVD. One case was taken from July 2007 and the other case was taken from July 2006. Although no representative case is shown for 2008 when Mexican radiosonde data was virtually nonexistent (significant PVDs were uncommon in 2008), the cases chosen from 2006 and 2007, respectively, were noteworthy for an absence of Mexican radiosonde data.

The July 2007 case featured a PVD that originated over the western Gulf of Mexico and moved northwestward across northeastern Mexico to extreme western Texas and southern New Mexico between 17-21 July 2007. The WRF model for this case was initialized at 1200 UTC 17 July 2007 and integrated through 0000 UTC 21 July 2007. The severe-weather outbreak occurred 60 h into the forecast. This case featured the development of a coherent PVD. As evidenced from Fig. 6.44 from Melino (2010), the PVD forecast track corresponded well with observations through 36 h. After that time the model forecast the PVD to move too quickly westward in comparison to observations (compare Figs. 6.44 and Fig. 6.45). A further comparison of Figs. 6.44 and 6.45 indicates that the WRF simulation failed to capture the strength of the westerly flow, and the implied associated cyclonic vorticity, over northern Mexico beyond 48 h. Discrepancies between the forecast and analyzed upper-level wind fields in Figs. 6.44 and 6.45 raise the possibility that analysis uncertainties over northern Mexico relating to the absence of Mexican radiosonde data may have contributed to the errors associated with the propagation speed of the northwestward-moving PVD. Although this WRF simulation was in the bottom half of our sample in terms of subjectively measured quality because the model forecast the fractured PVD to move too quickly westward, it would have provided useful guidance by alerting forecasters that a PV fracture would occur to the east of Arizona and that the resulting PVD would move westward and impact the state. This 25-km WRF model run forecast convection to occur over parts of extreme southern Arizona and eastern Arizona at forecast hours 60 and 61

(Fig. 6.47). Comparison of these 25-km WRF 60-61 h forecasts with the radar-indicated verification and the 4-km WRF 15-h and 18-h forecasts for 0300 UTC and 0600 UTC 21 July 2007 shown in Figs. 6.8 and 6.9 indicates that the 25-km WRF run would have provided potentially useful guidance to forecasters.

The second WRF model case study was taken from July 2006 and illustrates one of the better PV forecast fracture events in Melino's (2010) case study sample. The 25-km WRF was initialized at 1200 UTC 23 July and integrated through 0000 UTC 27 July. Comparison of Melino (2010) Figs. 6.50 and 6.51 shows that the model was nearly "perfect" through the 84-h forecast in predicting a PV fracture, the formation of a PVD from the PV fracture, and the initial westward track of the PVD, all of which occurred while the PVD was sampled by the US radiosonde network. The results from this 25-km WRF simulation shows that the model was capable of generating operationally useful forecasts (improved forecaster situational awareness) of the PVD fracture process, subsequent PVD formation, and the likely tracks of the PVDs. Based on the results of our numerical simulations, a schematic figure (Fig. 7.3 from Melino 2010) is presented of the critical ingredients necessary to produce a PVD-triggered significant MCS event.

Our initial idea, before we understood the characteristic pathways of propagating PVDs across the Southwest during the warm season, was that the absence of Mexican radiosonde data would prove detrimental to the analysis and prediction of PVD-triggered severe weather-producing MCSs in Arizona. Based on the sample of events we studied and modeled, our initial inference raised additional questions. Given that active severe weather events were more likely to be associated with westward-moving subsynoptic-scale PVDs that form via the PV fracture process well to the east of Arizona, it would appear that the upstream (to the east in this case) raob database over the US may at times be sufficient to permit upper-level subsynoptic flow details to be initialized properly. As a result, the dynamical processes associated with PV thinning, PV fracture, and PVD formation can often be well simulated by the current generation of operational numerical weather prediction models. However, when upper-level PVDs originate to the south of Arizona over northern Mexico and/or originate elsewhere but traverse parts of Mexico before influencing the summer weather in the Southwest, greater analysis and forecast uncertainties can arise from the 25 km WRF simulations. Although quantification of these analysis and forecast uncertainties based upon the tracks of PVDs are beyond the scope of this project, our preliminary results suggest a more comprehensive study might shed light on the value of Mexican radiosondes to warm season severe weather forecasts in the Southwestern US.

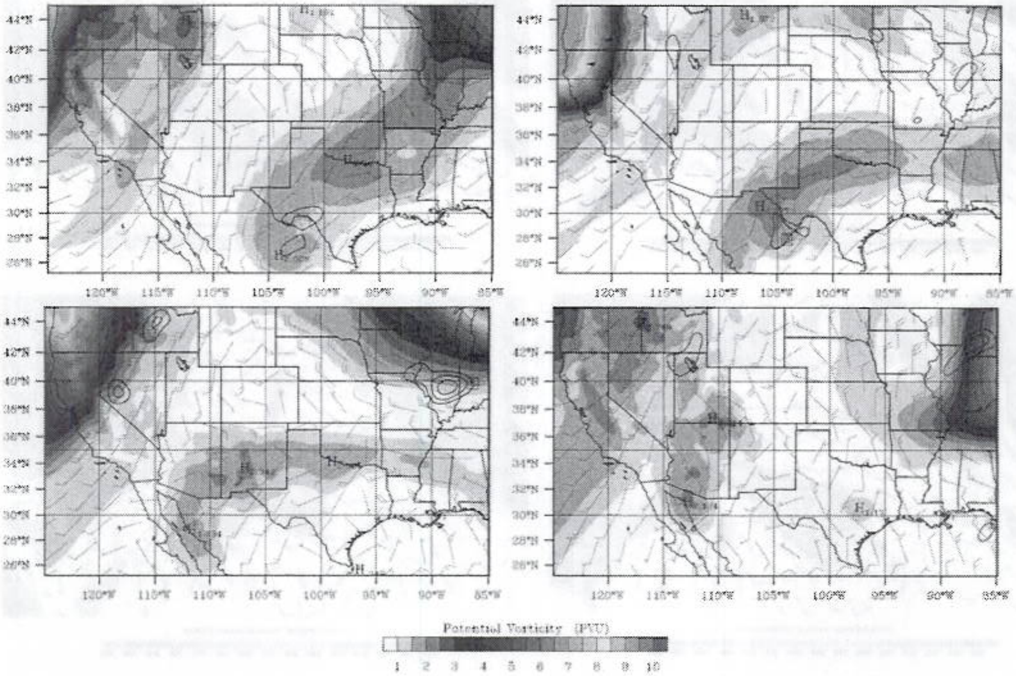


Figure 6.44 25-km WRF-simulated PV at 200 hPa (shaded, PVU) and 200 hPa winds (barbs, kt) for 0000 UTC 18 July 2007 (top left), 19 July 2007 (top right), 20 July 2007 (bottom left) and 21 July 2007 (bottom right).

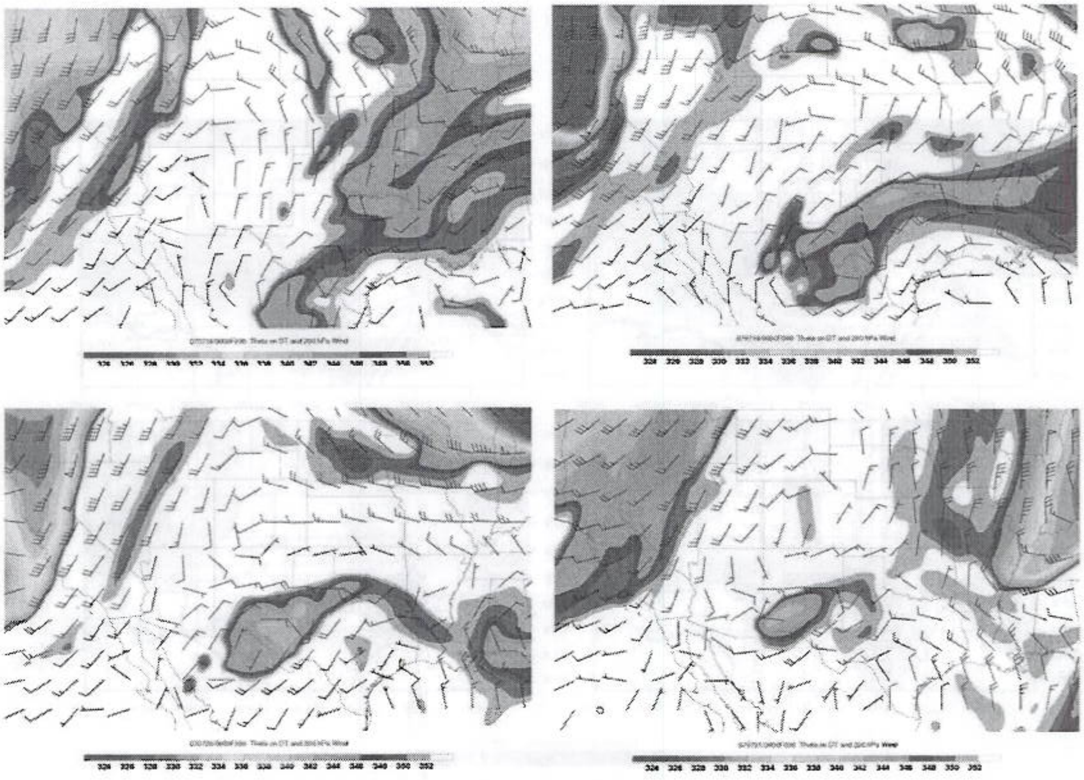


Figure 6.45 1.0° GFS dynamic tropopause potential temperature (shaded, K) and 200-hPa winds (barbs, kt) for 0000 UTC 18 July 2007 (top left), 19 July 2007 (top right), 20 July 2007 (bottom left) and 21 July 2007 (bottom right).

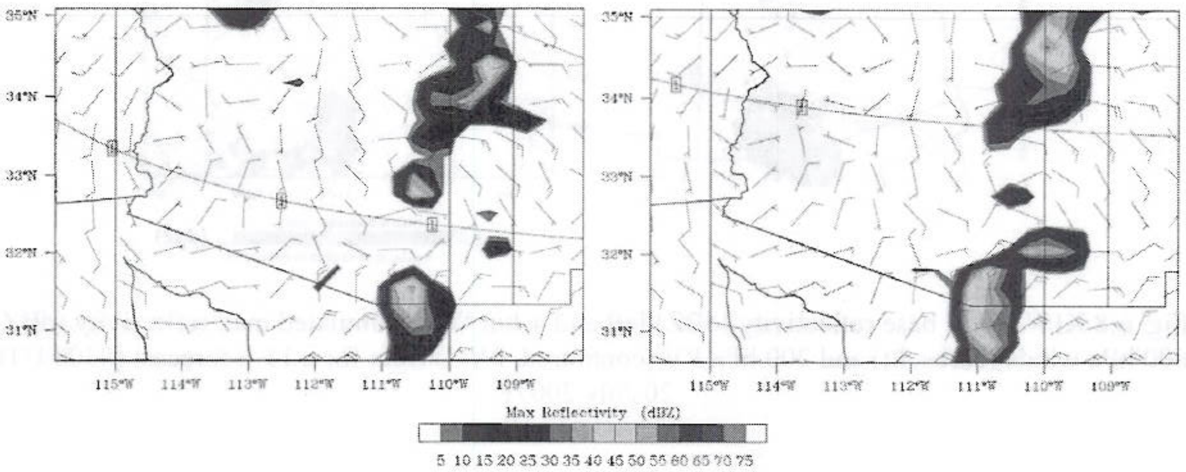
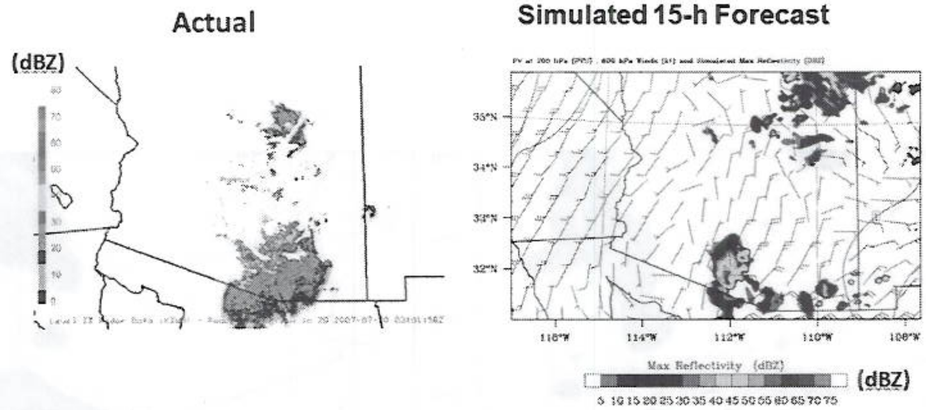
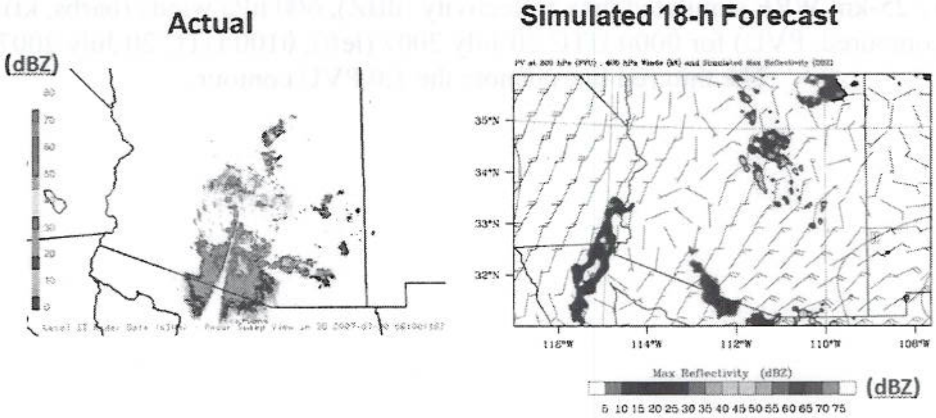


Figure 6.47 25-km WRF simulated max reflectivity (dBZ), 600 hPa winds (barbs, kt) and 200 hPa PV (contoured, PVU) for 0000 UTC 20 July 2007 (left), 0100 UTC 20 July 2007 (right). The thin red lines denote the 1.0 PVU contour.


Actual

Simulated 15-h Forecast

Fig. 6.8 KIWA 0.9° base reflectivity (dBZ) left and 4-km WRF simulated max reflectivity (dBZ), 600 hPa winds (barbs, kt) and 200 hPa PV (contoured, PVU) right for a 15-h forecast (0300 UTC 20 July 2007).


Actual

Simulated 18-h Forecast

Fig. 6.9 KIWA 0.9° base reflectivity (dBZ) left and 4-km WRF simulated max reflectivity (dBZ), 600 hPa winds (barbs, kt) and 200 hPa PV (contoured, PVU) right for a 18-h forecast (0600 UTC 20 July 2007).

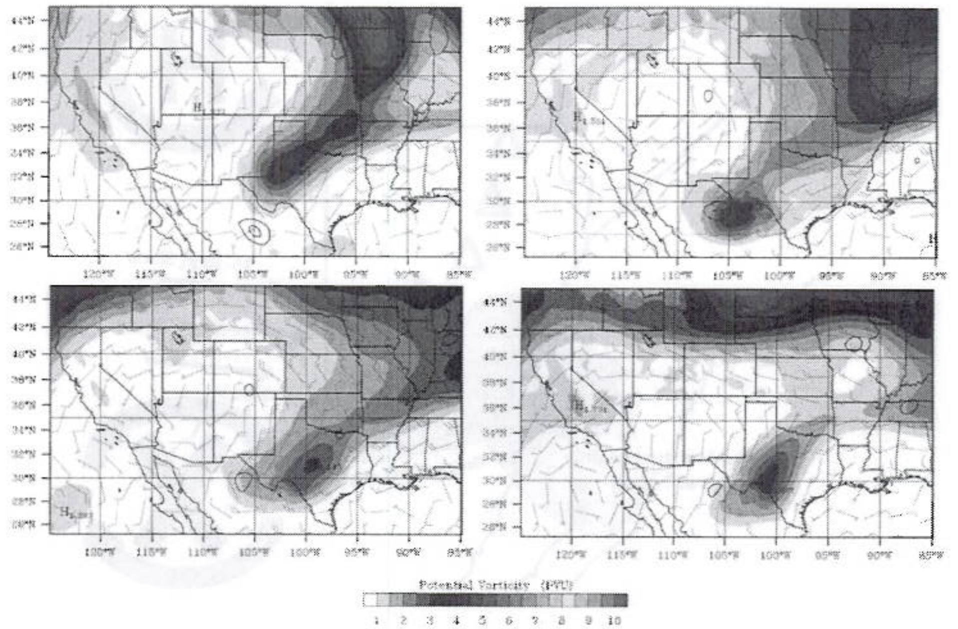


Figure 6.50 As in Fig. 6.44 except for 0000 UTC 24 July 2006 (top left), 25 July 2006 (top right), 26 July 2006 (bottom left) and 27 July 2006 (bottom right).

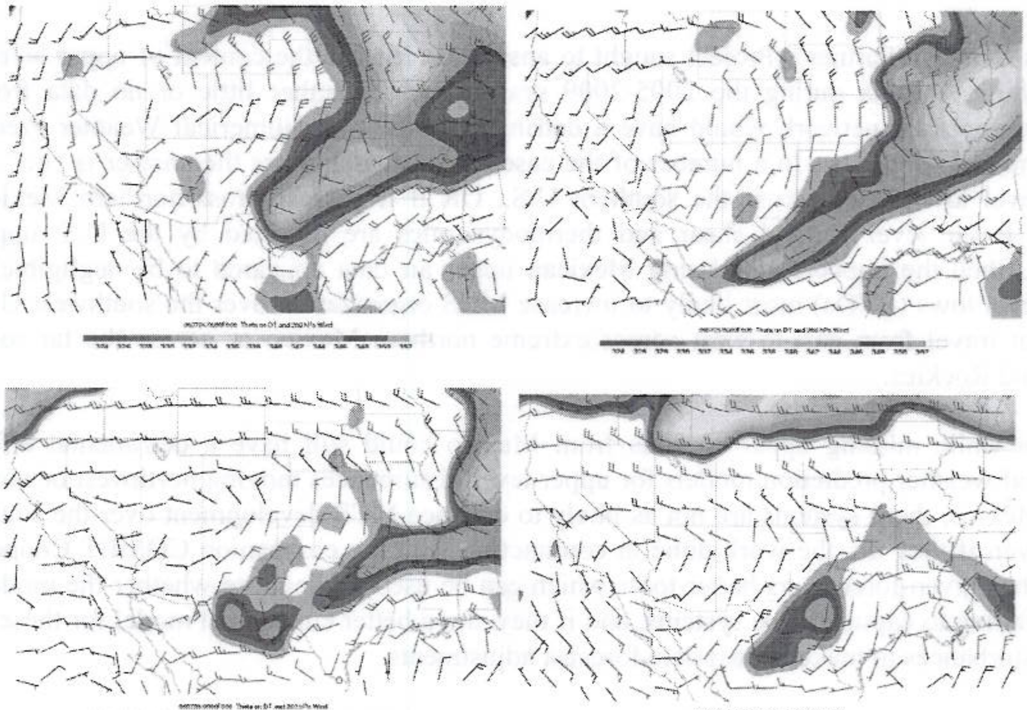


Figure 6.51 As in Fig. 6.45 except for 0000 UTC 24 July 2006 (top left), 25 July 2006 (top right), 26 July 2007 (bottom left) and 27 July 2006 (bottom right).

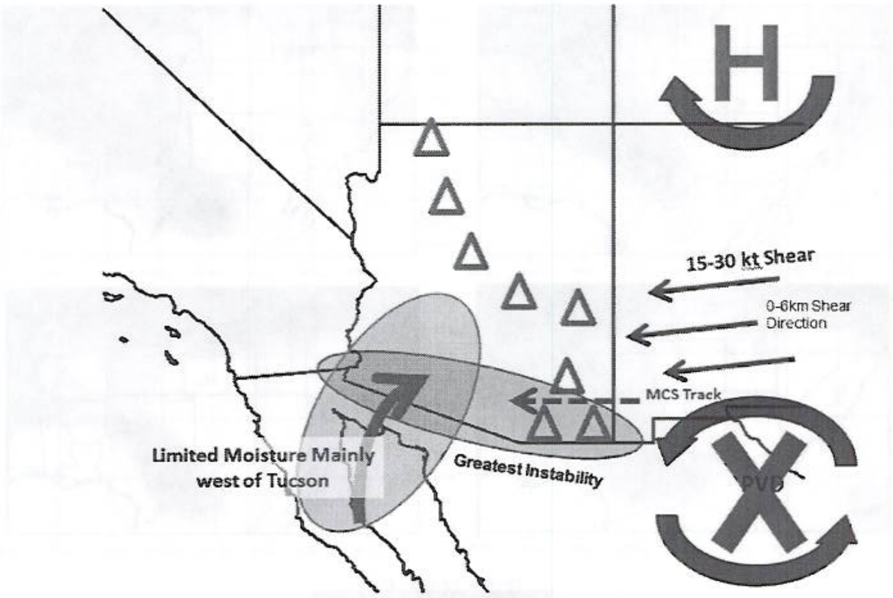


Fig. 7.3 Schematic of key ingredients necessary for the development of a substantial Southwest MCS event.

2.2 NWS WFO-TUS

This COMET Partner's Project sought to answer, at least in the context of upper level lows approaching Arizona during the 2005-2009 seasons, was whether little or no data from the Mexican upper air network would have a detrimental effect on Numerical Weather Prediction (NWP) model forecasts. In a number of the cases studied, it appears the answer is "no". If an upper level low passes across the southern U.S., OR if it passes across northern Mexico but impacts lower level vertical shear and thermodynamics are detected by the U.S. upper air network, then the impacts of missing Mexican upper air data appeared to be negligible. The upper-level lows (PVDs) most likely to increase MCS organization over the southwest U.S. are ones that travel from east-to-west across extreme northern Mexico or across the far southern Plains and Rockies.

Thus while missing upper air data from Mexico could still have a detrimental effect on numerical weather prediction models for upper level disturbances moving northwest or north out of the Mexico, these systems are not as likely to enhance MCS development over the southwest U.S. Even if they do, the work done in conjunction with the companion COMET Cooperative Project has given forecasters better tools which can be used to diagnose whether the models are indeed failing to capture these systems, and if they are, a better conceptual model for these upper level disturbances to make appropriate forecast adjustments.

2.2 SPC

In addition to the examining the impact of Mexican raob data, the SPC was also interested in the application of WRF models to the prediction of PVDs and model forecasts of deep convection during the monsoon season. The initial project work explored the performance of a number of different WRF model configurations, and also investigated use of a two-way nesting design where parameterized convection was used in the outer domain but not in the inner (convection-allowing) domain. The ability of the coarser resolution WRF model to predict the evolution of PVDs through 84 hrs using GFS data for ICs/LBCs is very encouraging. And while the explicit forecasts of deep convection are often probablematic from convection-allowing WRF configurations, the relationship between the PVDs and model generated convection appears to have substantial promise. This work relates directly to the operational use of high resolution WRF models for severe weather forecasting by SPC forecasters, and we will use these results to further explore daily WRF applications over the Southwest during the monsoon season.

SECTION 3: BENEFITS AND LESSONS LEARNED: OPERATIONAL PARTNER PERSPECTIVE

The benefits for this project were very similar to those of the companion COMET Cooperative Project. In addition to the forecasting benefits, NWS Tucson was honored to work with three very bright SUNY graduate students, demonstrate to them some of the challenges of forecasting in an operational environment during the monsoon, and share ideas on how potential vorticity diagnostics could potentially be used to track weak atmospheric disturbances that may not show themselves in traditional analyses. The communication aspects of this project also must be reemphasized. Projects like this provide a valuable skill-building exercise for graduate students participating in grant-directed research like this, particularly in an era where communication skills are rapidly becoming a key requirement for those seeking post-graduation employment.

This project also highlighted that sensitivity analyses like these can explicate situations in which missing upper air data can have a detrimental impact on NWP forecasts, and perhaps just as importantly, when they may not. It is important to note that *this study does not prove that missing Mexican upper air data is not a concern with respect to NWP performance.* However, it does highlight a specific situation in which missing upper air data may not have as adverse of an impact as one would normally expect, provided that the feature of interest is at least partially detected by the U.S. upper air network and noted in other remote sensing data like satellite imagery and automated aircraft observations.

This was also the first time at NWS entered into a companion COMET Partners' Project which studied a research challenge encountered in an ongoing COMET Cooperative Project. While the challenge was potentially a difficult one to solve, the additional project and student funding allowed us to research two significant operational forecasting challenges simultaneously, and to provide guidance to forecasters on not just the conceptual model of Potential Vorticity Disturbances, but also when the models may do surprisingly well even when upper air data may be missing in Mexico. Conducting the two projects in tandem was an efficient use of monetary and time resources for all concerned, and the research conducted in each project synergistically complimented the other.

SECTION 4: BENEFITS AND LESSONS LEARNED: UNIVERSITY PARTNER PERSPECTIVE

This project, and a related COMET Cooperative Project, supported three graduate students (Matusiak, Melino, and Sukup) and enabled them to complete M.S. theses and their M.S. degrees. Matusiak graduated in August 2009 and is employed by the NWS WFO in Charleston, WV. Melino and Sukup are graduating in August 2010. PI Bosart and his three project-supported graduate students continue to benefit professionally and educationally from our comprehensive project-related group research effort. The research findings related to the organization and evolution of convective systems in the Southwest are being used to sharpen and focus hypotheses about the origin and structure of monsoon-related convective weather systems and will be used in future endeavors. The research findings derived from WRF model simulations made by Melino (2010) in support of this COMET Partners Project have already been incorporated into PI Bosart's mesoscale meteorology teaching materials and adapted for his undergraduate and graduate classes. PI Bosart also gave a seminar on project-supported research findings at the SPC on 9 June 2010. His presentation will serve as the basis for a two-part classroom lecture on warm season severe convection. Finally, PI Bosart and graduate students Melino and Sukup had the opportunity to give a three-way oral presentation by video conference at the NWS Phoenix Weather Workshop on 25 May 2010. Again, the materials used for these presentations will be incorporated into UA mesoscale meteorology classes.

This project was also very valuable to UA because it enabled the three supported graduate students and PI Bosart to present their results at American Meteorological Society (AMS) and National Weather Association (NWA) conferences as well as regional and local conferences. For example, Tim Melino and Scott Sukup both attended and presented at the 34th annual meeting of the National Weather Association that was held in Norfolk, Virginia, from 17-22 October 2009. While in Norfolk, Melino, Sukup, and the PI met with Steve Weiss (SPC) and Erik Pytlak (WFO TUS) to review research progress and scope out new research. In particular, we talked about the best techniques for removing Mexican soundings from various cases of interest to determine the impact of the "missing" upper-air data on WRF model forecasts. PI Bosart gave an oral presentation on project findings at the 13th AMS Conference on Mesoscale Processes that was held in Salt Lake City, UT, from 17-20 August 2009. He will give another oral presentation on project findings at the upcoming 25th AMS Conference on Severe Local Storms to be held in Denver, CO, from 11-14 October 2010. Matusiak, Melino, and Sukup gave oral presentations on their results at the 34th and 35th Annual Northeastern Storm Conferences that were held in Springfield, MA, and Saratoga Springs, NY, respectively, on 6-8 March 2009, and 5-7 March 2010. The collective result of the student oral presentations supported by the COMET project was that the students gained considerable confidence in their ability to stand up in front of an audience and tell people what new science they learned, why it was important, and what its operational relevance was.

This project was also invaluable to the PI and his graduate students because working with the SPC and NWS/WFO-TUS participants gave us a much better appreciation of the operational aspects of the research and the operational constraints governing how to best transfer research to operations. It is extremely gratifying to see how the results from this research are being transferred to operations (e.g., the 2010 Phoenix Weather Workshop held on 25 May 2010) and how SPC forecasters have contributed their knowledge and experience to refining and improving the science and its application to operations.

SECTION 5: PUBLICATIONS AND PRESENTATIONS (LINKED WITH SEPARATE COMET COOPERATIVE PROJECT AS WELL)

Bosart, L. F., T. J. Melino, S. R. Sukup, J. E. Matusiak, S.J. Weiss, J. Racy, R. Schneider, D. Bright, and E. Pytlak. 2009: Dynamic tropopause mesoscale disturbances as triggers of warm season severe weather episodes in the Southwest. Oral presentation, *13th American Meteorological Society Conference on Mesoscale Processes*, 17-20 August 2009, Salt Lake City, UT.

Bosart, L. F., T. J. Melino, S. R. Sukup, J. E. Matusiak, S. J. Weiss, J. Racy, R. Schneider, D. Bright, E. Pytlak, and J. Matusiak 2010: The influence of upper-level potential vorticity disturbances on convection and severe weather in the Southwest. Part I: Oral presentation (invited) by video conference, *2010 Phoenix Weather Workshop*, 25 May 2010.

Bosart, L. F., T. J. Melino, S. R. Sukup, J. E. Matusiak, S. J. Weiss, J. Racy, R. Schneider, D. Bright, E. Pytlak, and J. Matusiak 2010: The influence of upper-level potential vorticity disturbances on convection and severe weather in the Southwest. Part I: Oral presentation (invited), *NOAA Storm Prediction Center*, Norman, OK, 9 June 2010.

Bosart, L. F., T. J. Melino, S. R. Sukup, J. E. Matusiak, S. J. Weiss, J. Racy, R. Schneider, D. Bright, E. Pytlak, and J. Matusiak 2010: Potential vorticity disturbances as a source of severe weather in the Southwest. Oral presentation, *25th American Meteorological Society Conference on Severe Local Storms*, 11-14 October 2010, Denver, CO.

Matusiak, J. E., 2009: Upper-level potential vorticity anomalies and their impact on warm season Southwestern United States severe weather. Oral presentation, *34th Annual Northeastern Storm Conference*, 6-8 March 2009, Springfield, MA., sponsored by Lyndon State College and the American Meteorological Society.

Matusiak, J. E., 2009: Upper-level potential vorticity disturbances and their impact on warm season Southwest United States severe weather. *M.S. thesis seminar presentation*, 22 June 2009, University at Albany, State University of New York, Department of Atmospheric and Environmental Sciences.

Matusiak, J. E., 2009: Upper-level potential vorticity disturbances and their impact on warm season Southwest United States severe weather. M.S. Thesis, Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, 194 pp.

Melino, T. J., S. R. Sukup, L. F. Bosart, J. E. Matusiak, S. J. Weiss, J. Racy, R. Schneider, D. Bright, and E. Pytlak 2010: The influence of upper-level subsynoptic-scale potential vorticity disturbances on severe weather in the Southwest. Part II: Case study. Oral presentation at *35th Annual Northeastern Storm Conference*, 5-7 March 2010, Springfield, MA., sponsored by Lyndon State College and the American Meteorological Society.

Melino, T. J., 2010: The influence of upper-level potential vorticity disturbances on severe weather in the Southwest: Case study and modeling results. *M.S. thesis seminar presentation*, 1 July 2010, University at Albany, State University of New York, Department of Atmospheric and Environmental Sciences.

Melino, T. J., 2010: The influence of upper-level potential vorticity disturbances on warm season convective organization in the desert Southwest. M.S. Thesis, Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, 217 pp.

Sukup, S. R., T. J. Melino, L.F. Bosart, J. E. Matusiak, S.J. Weiss, J. Racy, R. Schneider, D. Bright, and E. Pytlak. 2009: The influence of subsynoptic-scale dynamic tropopause potential vorticity disturbances on severe weather in the southwestern United States during the North American monsoon season. Oral presentation at the *34th Annual Meeting of the National Weather Association*, 17-22 October 2009, Norfolk, VA.

Sukup, S. R., T. J. Melino, L.F. Bosart, J. E. Matusiak, S.J. Weiss, J. Racy, R. Schneider, D. Bright, and E. Pytlak. 2009: The influence of upper-level subsynoptic-scale potential vorticity disturbances on severe weather in the southwestern United States. Oral presentation at *the Eleventh Northeast Regional Operational Workshop (NROW)*, 4-5 November 2009, Albany, NY, National Weather Service, University at Albany Department of Atmospheric and Environmental Sciences, and Amer. Meteor. Soc.

Suikup, S. R., 2010: The influence of upper-level potential vorticity disturbances on severe weather in the Southwest: A climatological perspective. *M.S. thesis seminar presentation*, 1 July 2010, University at Albany, State University of New York, Department of Atmospheric and Environmental Sciences.

Sukup, S. R., 2010: The influence of upper-level potential vorticity disturbances on convection and severe weather in the Southwest. M.S. Thesis, Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, 194 pp.

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

6.1: UA

As noted above, this project featured considerable interactions between the UA, SPC and WFO-TUS participants. These interactions occurred during conferences and workshops as summarized above, via email, and through occasional phone calls. PI-Bosart is a regular participant in the annual SPC Testbed Experiment. Over the lifetime of the project he interacted with the SPC participants during his visits through direct talks and seminars. He also took advantage of his participation in the AMS hurricane and tropical meteorology conference, held 10-14 May 2010 in Tucson, AZ, to discuss project-related research and operational findings with Erik Pytlak.

6.2: NWS WFO-Tucson

NWS Tucson interacted with all SUNY and SPC parties frequently throughout the three year project. This frequent interaction, sharing of possible investigatory cases, and meetings at SPC, NWS Tucson, and national conferences allowed us to evaluate progress, offer suggestions when concerns arose, and helped to lead to a successful conclusion.

6.2: Storm Prediction Center

SPC collaborated routinely with the PI, UA students, and WFO-TUS during the project, especially at workshops and conferences when informal discussions and planning meetings took place. A key positive aspect of the project was the enhanced spirit of collaborative investigation where the academic and operational partners were focused on finding scientifically-based results that benefit all parties (forecasters, students, and PI).