Final Report for NSF Award ATM- 0530814

Storm-Scale Quantitative Precipitation Forecasting Using Advanced Data Assimilation Techniques: Methods, Impacts and Sensitivities

Dr. Ming Xue[1,2], Principal Investigator
Dr. Keith Brewster[1], Co-Principal Investigator
Dr. Jidong Gao[1], Co-Principal Investigator
Dr. Alan Shapiro[1,2], Co-Principal Investigator
[1]Center for Analysis and Prediction of Storms and [2]School of Meteorology
University of Oklahoma

120 David Boren Blvd
Norman OK 73072

Funding Period: December 1, 2005 – November 30, 2009, including no cost extension for December 1, 2008 – November 30, 2009

December 2009

Contacting e-mail: mxue@ou.edu

1 Introduction

Our original proposal proposed to work in the following areas: (a) Initial and boundary condition sensitivity studies and adjoint applications and development of ARPS 4DVAR; (b) Initialization and prediction of convective storms using 3DVAR and complex cloud analysis and the impact and refinement of cloud analysis procedures; (c) 3DVAR analysis and assimilation of GPS slant-path integrated water vapor data and their impact on QPF; (d) Ensemble Kalman filter-based assimilation of radar and other high-resolution observations for mesoscale and storm-scale analysis and prediction; (e) High-resolution simulation and analysis of convective initiation cases of IHOP_2002; (f) Sensitivity of QPF to microphysical parameterizations. Because of the reduction by about ¼ from the originally proposed budget and the removal of support for one graduate student, we stated in our impact statement that the research in areas (b) and (f) will be limited under the support of this grant, and we will not be able to work on 4DVAR data assimilation in area (a).

In spite of the significantly reduced budget, we have been able to make significant progresses in most of the proposed research areas, and in some cases with leverages from other sources of support, including NSF Graduate Fellowship for one of the graduate students. Due to the departure of two post-docs working on this project and the hiring of new personnel, and the time needed to publish the research findings, we have requested a one year no cost extension for this grant. Specific achievements of this project so far, with emphasis on achievements in year three of the project, are summarized in the following sections.

2 Specific Accomplishments

2.1 Initial Condition Sensitivity Study Using Very Large Ensembles

In Martin and Xue (2006), sensitivity analyses were done using very large (several thousand member) ensembles of forward model runs that perturb the initial model fields one small patch at a time, so that sensitivity maps of the subsequent forecast fields (e.g., precipitation) to the initial condition (different variables at different regions) can be calculated. This above work has been extended more recently with new approaches that require fewer ensemble members (Martin and Xue 2010a; 2010b). In this study, a large number (~2000) of forward model runs with randomly perturbed initial fields are made and the correlation (or sensitivity) between forecast quantities and initial fields are calculated statistically. The technique is found to accurately calculate three-dimensional initial condition sensitivity fields without the need for linearizing the model (as is required by an adjoint). The new method is much more efficient than that of the earlier method of Martin and Xue (2006).

2.2 Data simulation and prediction of tornadic thunderstorms using level-II radar data with ARPS 3DVAR and cloud analysis

The ARPS 3DVAR-cloud analysis combination is shown to be efficient and effective through a number of case studies for initializing convective storms (Hu et al. 2006a; Hu et al. 2006b). Typically, rapid update cycles at 5 to 15 minutes intervals are used. Hu and Xue (2007a) examined various configurations of the intermittent 3DVAR-cloud analysis data assimilation procedure for the 8 May 2003 Oklahoma City tornadic thunderstorm case, using a nested 3 km

grid. The results also show that when the data from a single Doppler radar is assimilated with properly chosen assimilation configurations, the model is able to predict the evolution of the 8 May 2003 Oklahoma City tornadic thunderstorm rather accurately for up to 2.5 hours.
More recently, Hu and Xue (2007b) obtained a successful prediction of the tornado of 8 May 2003 in the OKC area, using nested grids of up to 50 m horizontal resolution, and by assimilating radar data on a 1-km grid over a 70-min time window. The tornado prediction results are also reported in Xue et al. (2007a); and two journal articles for more in-depth analysis are under preparation (Hu and Xue 2010; Xue and Hu 2010). Most recently, for this same case, M.S. student Edward Natenberg, advised by project co-PI Jidong Gao, completed a study examining the effectiveness of ARPS 3DVAR in analyzing data from multiple WSR-88D radars and from the Oklahoma City TDWR radar, for the initialization of the same May 8, 2003 OKC case. It is found that the use of additional radars helps improving wind field analysis significantly, especially in the local radar 'cone of silence' and in regions where dual-Doppler radar coverage is available. It is shown that the forecasts resulting from a single time analysis are of similar quality as those obtained by Hu and Xue using single radar and multiple assimilation cycles. A M.S. thesis was completed based on this work (Natenberg 2008). At the same time, Ph.D. student Guoqing Ge continued to examine the impact of additional equation constraint on the 3DVAR analysis of this and other cases. This grant provided one-year RA support for Guoqing Ge. A paper has resulted from this partial support (Ge et al. 2010).

2.3 3DVAR analysis of water vapor field from GPS slant-path and surface network data

Ph.D. student, Haixia Liu developed a new univariate 3DVAR system for analyzing water vapor from GPS slant-path water vapor observations (Liu and Xue 2006). Unique aspects of this work include the use of flow-dependent background error structures that are modeled by anisotropic explicit or recursive spatial filters. Observation system simulation experiments (OSSEs) performed for an IHOP dryline case (19 June 2002) clearly demonstrated the significant positive impact from the use of the flow-dependent background error. The analysis system was also shown, among other things, to be robust, even in the presence of observational errors and/or with a poor analysis background. The recursive filter version of the anisotropic background error has also been implemented in our 3DVAR system, improving its computational efficiency. Analyses with the recursive filter show slightly better quality than those with an explicit filter. We believe this result is due to the improved positive definiteness property of the recursive filter. The results are summarized in an accepted manuscript (Liu et al. 2007a).

Using the realtime forecast data set from the dryline case of June 19, 2002 as the 'truth', Ph.D. student Haixia Liu demonstrated that a 3DVAR system with proper specification of background error structure is capable of accurately analyzing 3D water vapor fields from simulated GPS slant-path water (SWV) observations (Liu 2007), and the results are improved when using flow-dependent background error, realized in the 3DVAR system using anisotropic explicit (Liu and Xue 2006) or recursive (Liu et al. 2007a) filters. OSSEs (Observing System Simulation Experiments) using the control simulation of Liu and Xue (2008) as the truth further demonstrated the positive impact of SWV and mesoscale surface network data on quantitative precipitation forecasts (Liu 2007; Xue and Liu 2010).

2.4 Ensemble Kalman filter data assimilation research

Ph.D. student and then post-doc, Mingjing Tong, developed an ensemble Kalman filter (EnKF) data assimilation (DA) system within the APRS framework (Tong 2006). Tong and Xue (2005), showed, for the first time, that multiple microphysical species within a single-moment ice microphysics scheme can be retrieved accurately in an OSSE framework. Xue et al. (2006) enhanced this EnKF system and applied it to the assimilation of assimilation CASA network data.

Through state vector augmentation, Tong and Xue (2008b, a) further demonstrated, for the first time, that up to five microphysics DSD parameters can be estimated together with the state variables using radar reflectivity data. Tong (2006) further applied this EnKF system to the May 29, 2004 Oklahoma City (OKC) tornadic thunderstorm cases, using data from one or two nearest WSR-88D radars. For real cases, the presence of model error and error in the storm-environment poses significant changes to obtaining good EnKF analysis, and Tong and Xue (2007) investigate the possible sources of error with OSSEs similarly configured with the real case settings. It was shown that the use of multiple microphysics parameterization schemes in the ensemble system and the introduction of microphysical parameter perturbations in the parameterization schemes can alleviate some of the negative impact of microphysical parameterization error. A journal article is under preparation to report the latest findings.

The ARPS EnKF system has been recently enhanced, under the support of other grants, to include conventional observations (Xue et al. 2010a) and ability of assimilate polarimetric radar data (Jung et al. 2008b; 2008a). Xue et al. (2007b) discusses the proper way to model reflectivity errors in OSSEs. The EnKF system plays an important role in the NSF ERC CASA (Center for Collaborative Adaptive Sensing of Atmosphere) project, as a tool to demonstrate the value of CASA's high-density adaptively sensed data, and two papers demonstrating the value of CASA radar data assimilated using the ARPS EnKF system are being finalized for submission (Snook et al. 2010b, a).

In Xue, et al. (2009), a new approach to dealing with attenuated radar reflectivity data in the data assimilation process is developed and tested with simulated data using the EnKF. This approach differs from the traditional method where attenuation is corrected in observation space first before the corrected data are assimilated into numerical models. Instead, the attenuation correction is built into the data assimilation system by calculating the expected attenuation within the forward observation operators using the estimated atmospheric state. Being part of a data assimilation system based on optimal estimation theory, error and uncertainty information on the observations and prior estimate can be effectively utilized, and additional observed parameters, such as those from polarimetric radar, can potentially be incorporated into the system for state estimation and attenuation correction. Tests with simulated X-band reflectivity data for a supercell storm show that the proposed attenuation correction procedure is very effective – the analyses obtained with such a procedure using attenuated data are almost as good as those obtained using un-attenuated data.

Mingjing Tong's Ph.D. Dissertation (Tong 2006) won the sole OU's Provost Ph.D. Dissertation Prize in the Science and Engineering category in 2006, and Tong and Xue (2008a) won SOM Lilly Award for Best Ph.D. Paper in 2007.

Gao and Xue (2008) developed an efficient dual-resolution EnKF data assimilation algorithm in which observations are assimilated on a single high-resolution grid using flow-dependent background error covariance estimated from a lower-resolution ensemble.

2.5 Data impact and convective initiation studies for IHOP cases

Xue and Martin (2006a, b) performed a detailed simulation and diagnostic study on the convective initiation (CI) mechanism of the 24 May 2002 dryline case, and identified the important role played by fine-scale horizontal convective rolls (HCRs) and their interaction with the dryline in determining the exact location for initiation. Another convective initiation case of IHOP_2002, that of 12-13 June that involved dryline and MCS outflow boundary and multiple CIs has also been simulated with remarkable accuracy by (Liu and Xue 2008). A detailed analysis (Xue et al. 2010b) reveals the subtle role of the interaction of a secondary mesoscale convergence zone with HCRs, for the CI that occurred to the southeast of dryline-outflow boundary triple points. In both cases, high-frequency data assimilation cycles including all available observations are shown to be important (Martin and Xue 2007; Liu and Xue 2008), so is the model resolution. A preliminary study (Martin and Xue 2007) tries to further improve the results of Xue and Martin (2006a) by using higher spatial resolutions and more data. It also investigated the reason for too early initiation when more data are assimilated in more frequent cycles.

In the control experiment of Liu and Xue (2008) a secondary initiation of cells due to the collision between the main outflow boundary and the gust fronts developing out of model-predicted convection earlier is also captured accurately about 6 to 7 hours into the prediction.

Following a similar methodology applied the convective initiation cases of May 24 and June 12 from IHOP, except for the use of the ARPS 3DVAR instead of ADAS (ARPS Data Analysis System), post-doctoral scientist Qiwei Wang is studying the convective initiation process involved in the third intensely observed convective initiation cases from IHOP (Wang and Xue 2010; Xue and Wang 2010). More specifically, this case is simulated using the Advanced Regional Prediction System (ARPS) with a 1-km horizontal resolution grid nested inside a 3-km domain. The case involves three distinct CIs accompanying a cold front-dryline interaction. Standard as well as special upper-air and surface observations collected during the IHOP_2002 are analyzed to obtain the initial condition. The control experiment initialized from an ARPS 3DVAR analysis at 1800 UTC June 2002 captured the initiation of the three groups of convective cells rather well. The first focused CI starting in the front-dryline transition zone over southeast Colorado is simulated about 5 km west of the observed counterpart with a 20 minute delay. The timings of the second CI forming along the dryline over northwest Kansas, and the third CI locating further north along the cold front over south-central Nebraska, are accurate to within 30 minutes with location errors of 80 and 60 km respectively (Fig. 1). The general evolution of the three predicted CIs also verifies well.

The general deepening of the well-mixed moist boundary layer is found to be essential to the CIs. Mesoscale convergence associated with the confluent flow around the dryline and/or the cold front produces obvious uplift of the moisture layer and provides favorable conditions for the CI there. The model prediction of these features verifies very well against aircraft dropsonde observations available for the CI in western Kansas (Fig. 2). The initial cell initiations are located near major low-level moisture convergence bands but with different relative positions, suggesting that the actual triggering of deep moist convection at specific locations depends on localized forcing. The localized forcing is often due to enhanced convergence associated with horizontal convective rolls and their interactions with mesoscale dryline and/or cold front circulations. The exact processes of the CIs is analyzed in detail in Xue and Wang (2010).

In addition to the data assimilation experiments for the IHOP cases using the ARPS 3DVAR and the ARPS Data Analysis System (ADAS) earlier, results have been obtained using the ARPS

EnKF system for assimilating the same set of data. In general, the forecast results are improved over the 3DVAR or ADAS results, and two manuscripts are under preparation based on these results.

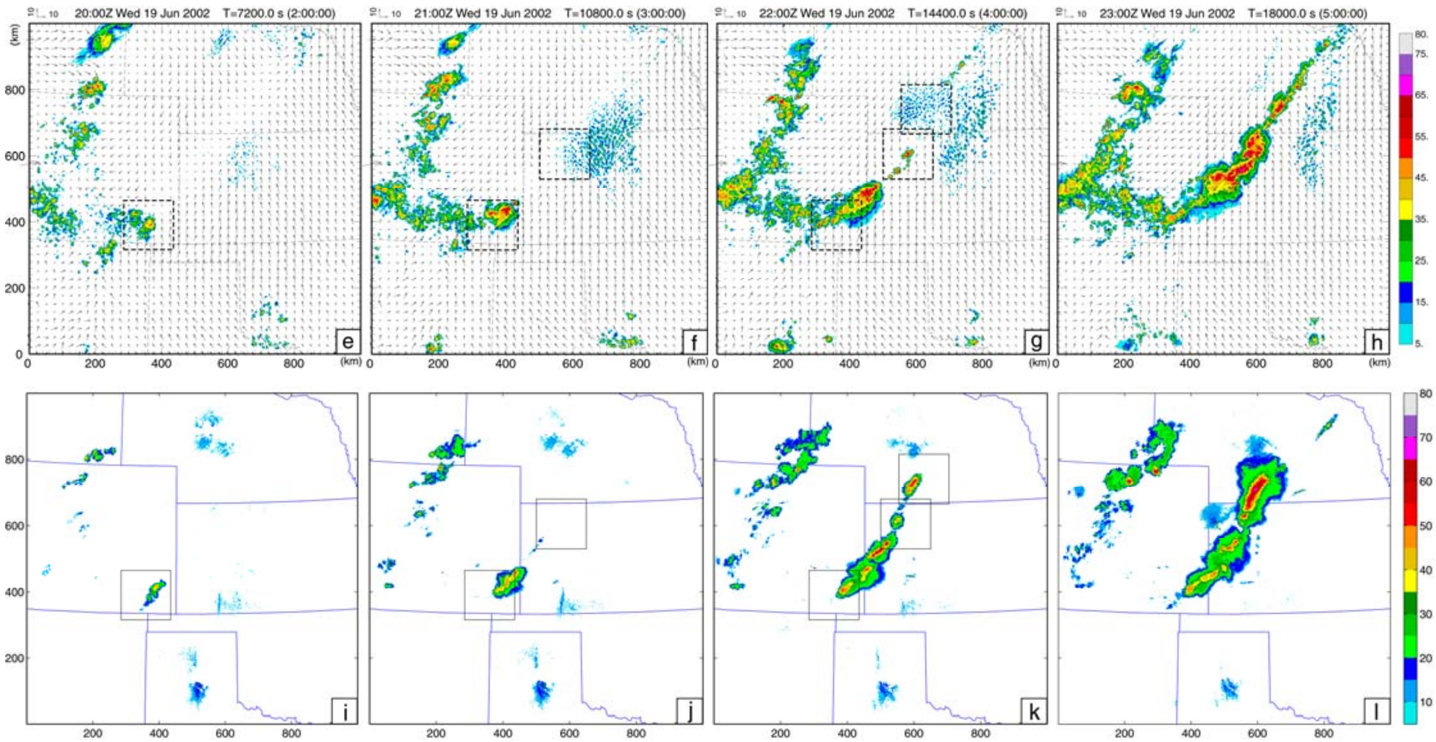

Fig. 1. ARPS 1-km forecast composite reflectivity (color shaded) of control data assimilation experiment together with surface wind vectors at (e) 2000, (f) 2100, (g) 2200, and (h) 2300 UTC 19 June 2002. The plots in (i)-(l) are the corresponding observed composite reflectivity fields. The small square boxes in the figure are over the three regions of convective initiation.

2.6 The role and effects of microphysical processes in tornadic storms

Snook and Xue (2008)performed idealized simulations of tornadogenesis in supercell storms using a grid of 100 m spacing. The cold pool intensity and low-level storm dynamics are found to be very sensitive to the intercept parameters of rain and hail drop size distributions (DSD), that often take assumed values in commonly used single-moment microphysics schemes. DSDs favoring smaller (larger) hydrometeors result in stronger (weaker) cold pools due to enhanced (reduced) evaporative cooling/melting over a larger (smaller) geographic region. Sustained tornadic circulations of EF2 intensity are produced in two of the simulations with relatively weak cold pools. When the cold pool is strong, the updraft is tilted rearward by the strong, surging gust front, causing a disconnect between low-level circulation centers near gust front and the mid-level mesocyclone. Weaker cold pool cases have strong, sustained, vertical updrafts positioned near and above the low-level circulation centers, providing strong dynamic lifting and vertical stretching to the low-level parcels and favoring tornadogenesis. Such a process by which the cold pool strength determines the tornadogenesis potential had not been documented before and is believed to represent an advancement in tornadogenesis theory.

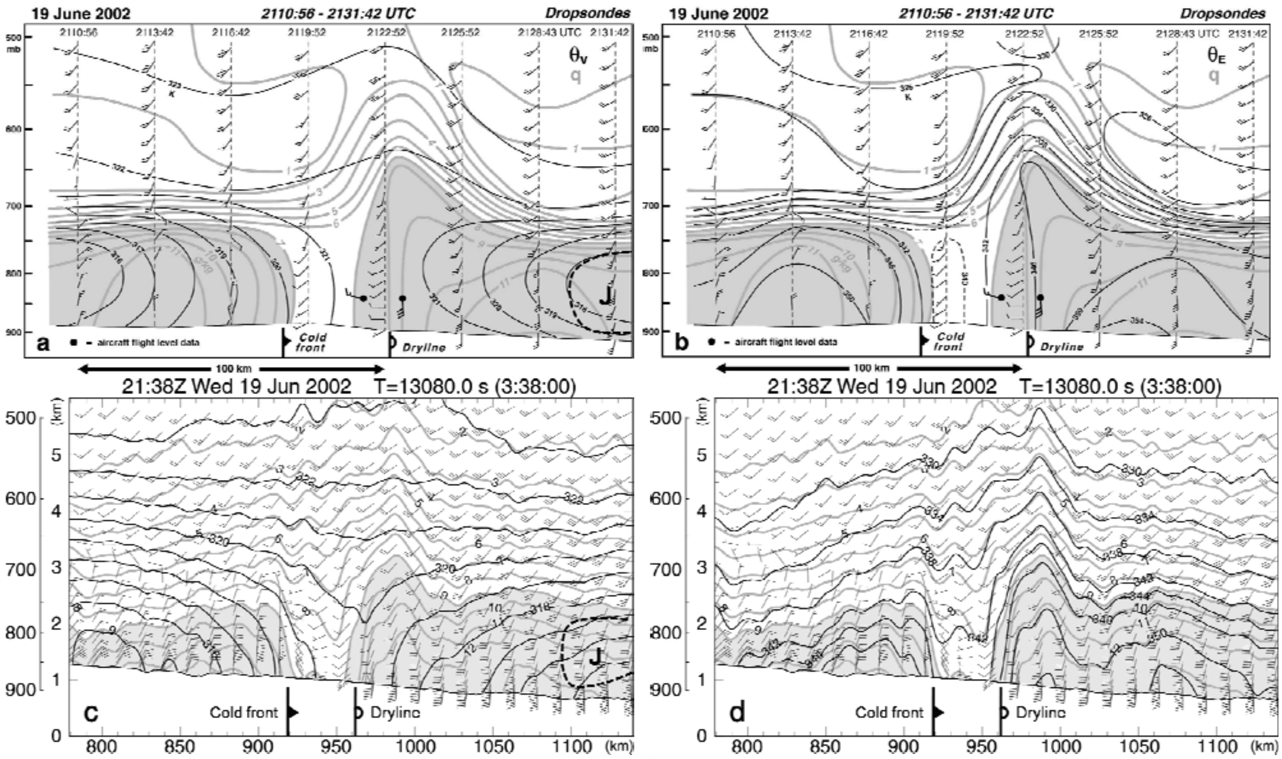

Fig. 2. Observed (upper panels) and model-predicted (lower panels) horizontal winds, water vapor mixing ratio (gray lines), overlaid with virtual potential temperature (left panels) and equivalent potential temperature (right panels) for the convective initiation event in western Kansas that we intensively observed during IHOP_2002. The observational plots are based on a series of aircraft dropsondes along a straight flight path (reproduced from Murphey et al. 2006) and the cross section is in a northwest-southeast direction normal to the dryline.

Given the large uncertainty in DSD parameters used single-moment microphysics schemes, a new multi-moment ice microphysics package from Milbrandt and Yau (2005a; b, MY05 hereafter) was recently implemented inside the ARPS. The package contains single, double, triple (or 1, 2 and 3) moment options and a 2.5-moment option (referred to as MY1, MY2, MY3 and MY2.5 hereafter) in which the shape parameter in the gamma distribution is diagnosed. In the triple moment case, the model predicts total number concentrations (zero moment), mixing ratios (3rd moment) and equivalent reflectivities (6th moment) of all (2 liquid, 4 ice) microphysical species.

A number of technical issues had to be resolved before the MY schemes produce reasonable solutions in the ARPS implementation. Further, the WRF single-moment six-category ice physics scheme (WSM6, Hong and Lim 2006) and its modified version that diagnoses intercept parameters from mixing ratios (Zhang et al. 2008) have also been implemented in the ARPS. These schemes provide us the capabilities to, among other things, examine the sensitivities of QPF to microphysics of different degrees of sophistication.

Ph.D. student Daniel Dawson applied the MY scheme to the May 3rd, 1999 OKC F5 tornado case, initializing either using a single sounding or real observations (Dawson et al. 2007; 2008).

A journal article summarizing the realized simulation results have been accepted for publication (Dawson et al. 2010)

In Dawson et al. (2010), single-sounding idealized simulations of the 3 May 1999 storms are conducted at various horizontal grid spacings ranging from 1 km to 250 m, using a sounding extracted from a prior 3 km grid spacing real-data simulation. The multi-moment (MM) bulk microphysics parameterization (BMP) scheme is evaluated and compared with traditional single-moment (SM) schemes. The emphasis is placed on the impact of microphysics on cold pool strength and structure, and on the overall reflectivity structure of the simulated storms. It is shown through the use of microphysics budget and trajectory analyses within the low level downdrafts, that several important advantages of MM schemes over SM schemes lead to a weaker and smaller cold pool, and better reflectivity structure, particularly in the forward flank region of the simulated supercells. The results of the MM simulations are more consistent with the observed (from both fixed and mobile mesonet platforms) thermodynamic conditions within the cold pools of the discrete supercells of the 3 May 1999 outbreak.

Real-data simulations using multi-moment bulk microphysics of the 3 May 1999 Oklahoma tornado outbreak were performed and reported in Dan Dawson's Ph.D. dissertation (Dawson 2009), with manuscripts summarizing the results under preparation. With the real data study, a telescoping one-way nested grid structure is used, with the two outer grids (3 km and 1 km grid spacing) employed to capture the mesoscale and storm-scale environments, respectively. On the 3 km grid, hourly data assimilation cycles are performed from 1800 UTC 3 May 1999 to 0300 UTC 4 May 1999, with conventional and satellite data assimilated using the ARPS 3DVAR system. On the 1 km grid, 10 minute assimilation cycles are performed from 2100 UTC 3 May 1999 to 2230 UTC 3 May 1999, to cover the initial development of the first two tornadic supercell storms of the outbreak. Conventional, satellite, Oklahoma mesonet, and NEXRAD Level II radar reflectivity and radial velocity data were all assimilated during this assimilation window. A forecast was launched from the final 2230 UTC analysis time, ending at 0300 UTC. The overall motion and evolution of the two storms was well-predicted (not shown).

The two inner grids (250 m and 100 m grid spacing) are employed to capture the development of sub-storm scale features such as the mesocyclone (250 m grid) and the tornado itself (100 m grid), with a focus on the main storm of the outbreak, that produced a long-lived F-5 intensity tornado from parts of Moore, OK to Oklahoma City, OK. The 250 m grid was nested directly inside the 15 minute forecast of the 1 km experiment, with no additional data analysis performed. Both the 250 m and 100 m runs were run out to 0100 UTC 4 May 1999. Several different microphysics schemes or variations are examined on both the 250 m and 100 m grids. These include the 1-, 2-, and 3-moment versions of the Milbrandt and Yau multi-moment bulk microphysics scheme (MY1, MY2, and MY3, respectively). Two variations of MY1 are tested (denoted MY1A and MY1B), each with a different value of the intercept parameter for rain: $N_{0r} = 8.0 \times 10^6$ m^{-4} and $N_{0r} = 4.0 \times 10^5$ m^{-4}, respectively. The former represents a rain DSD skewed toward relatively smaller drops, and the latter a DSD skewed toward relatively larger drops. In addition, a version of the MY2 scheme where the shape parameter α is diagnosed (MY2DA), rather than fixed is being tested.

The results indicate that the MY3 scheme does the best job of capturing the development, longevity, intensity, and track of the tornado on the 100 m grid (Fig. 3). The predicted tornado forms approximately 45 minutes later than the observed tornado, and accordingly, its track is shifted north and east of the observed tornado. MY1B, MY2, and MY2DA all produce a tornado as well, but the tornadogenesis is further delayed relative to MY3. MY1A fails to produce any significant low-level rotation throughout the forecast period, due to significant amounts of cold outflow undercutting the updraft of the storm. Further analysis of the results is being performed, including dynamical analyses along trajectories of the vertical vorticity equation as it relates to the model tornadogenesis and maintenance, and the results will be reported in future journal articles.

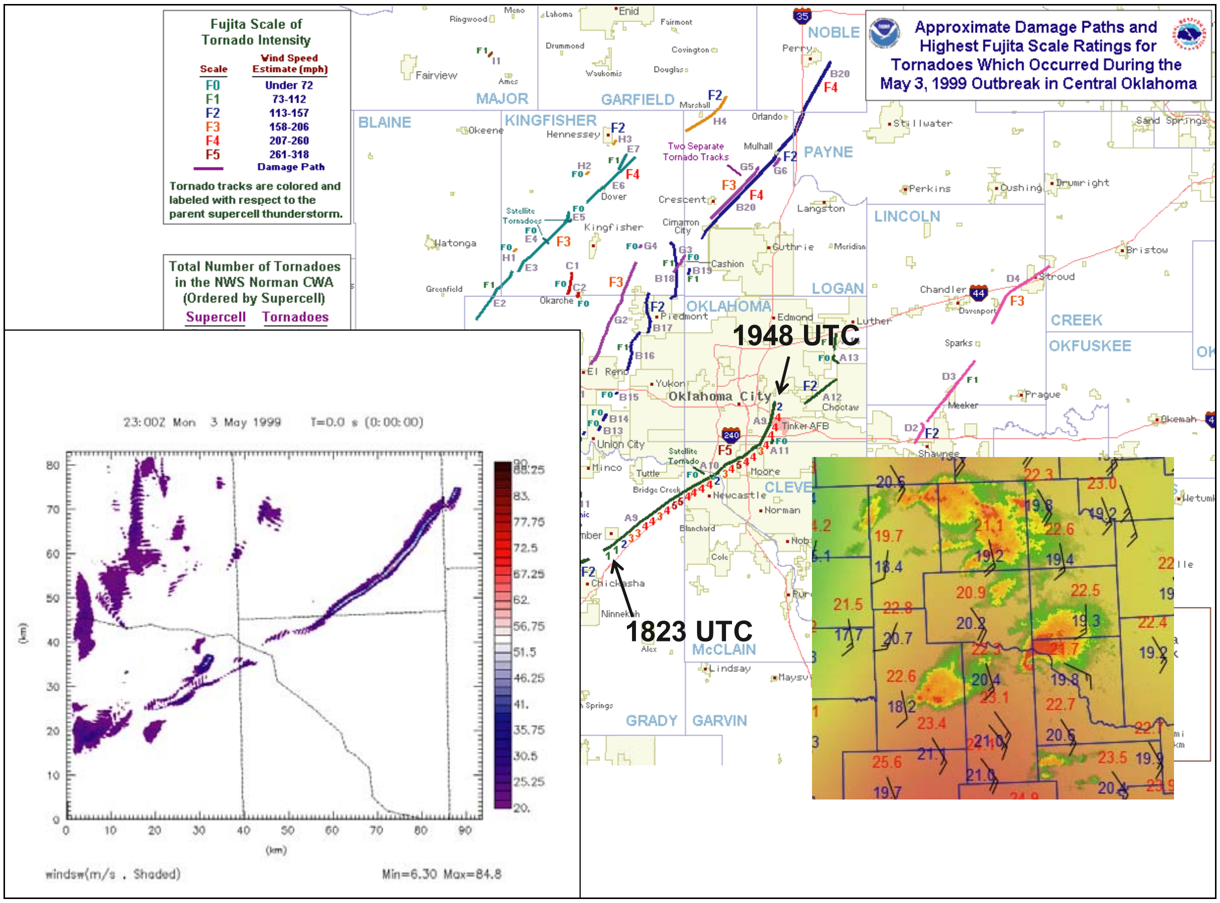

Fig. 3. Observed OKC F5 tornado track (center), model forecast tornado track (maximum surface wind speed swath) using the MY3 scheme at 100 m grid spacing (lower-left insert), and observed reflectivity and surface conditions at 0000 UTC (lower-right insert). The start and end times of the F5 tornado are indicated.

2.7 Other studies under the partial support of this grant

Other refereed publications under the complete or partial support of this grant includes: Sheng et al. (2006) on the impact of assimilating radar data on the prediction of various precipitation systems, Gao et al. (2006; 2008) on the effect of refractivity on radar paths calculations, Martin and Shapiro (2005; 2007) on the impact of radar tilt and ground cluster on clear-air wind measurements and on the discrimination of bird and insect clear-air radar echoes, Xu et al. (2008) on a time-expanded sampling approach for EnKF, and Tanamachi et al. (2008) investigated rapid upper boundary layer drying and moistening events during IHOP by using both observational and the ARPS model simulated data. The following papers by the PIs (Xu et al. 2006; Limpasuvan et al. 2007; Liu et al. 2007b; May et al. 2007; Cheong et al. 2008; Gao et al. 2008; Potvin et al. 2009; Shapiro et al. 2009; Jung et al. 2010b, a; Schenkman et al. 2010b, a; Xue et al. 2010c) also acknowledge the support of this grant.

3 Education and Training

This research grant provided complete or partial support for 4 Ph.D. students (Mingjing Tong, Haixia Liu, Daniel Dawson, Guoqing Ge) and five post-doctoral scientists for different lengths of time (William Martin and Mingjing Tong, Qiwei Wang, Kun Zhao, Daniel Dawson). Mingjing Tong and Haixia Liu completed their Ph.D. degrees in 2006 and 2007 respectively, and Daniel Dawson completed in 2009. William Martin took a Science and Operations Office (SOO) position at a National Weather Service Forecasting Office, while Ming Tong and Haixia Liu both now work at the Environmental Modeling Center of NCEP (National Centers for Environmental Prediction). Daniel Dawson is currently a National Research Council post-doc working at the National Severe Storms Lab.

4 Dissertations Completed

Tong, M., 2006: Ensemble Kalman filer assimilation of Doppler radar data for the initialization and prediction of convective storms, Ph.D. Dissertation, School of Meteorology, University of Oklahoma, 243 pp.

Liu, H., 2007: Analysis of GPS Slant-path Water Vapor Observations using 3DVAR with Anisotropic Filters and Their Impact on the Prediction of Convective Initiation and Precipitation, School of Meteorology, University of Oklahoma, 188 pp.

Dawson, D., 2009: Impacts of single- and multi-moment microphysics on numerical simulations of supercells and tornadoes of the 3 May 1999 Oklahoma tornado outbreak, School of Meteorology, University of Oklahoma, 173.

The Ph.D. dissertation of Mingjing Tong (Tong 2006) won the sole OU's Provost Ph.D. Dissertation Prize in the Science and Engineering category in 2006.

Tong and Xue (2008a) won School of Meteorology Douglas Lilly Award for Best Ph.D. Paper in 2007.

Liu et al (2007b) won School of Meteorology (SOM) Douglas Lilly Award for Best Ph.D. Paper in 2006.

5 References cited, with those completed under complete or partial support of this grant proceeded with a '*'

*Cheong, B. L., R. D. Palmer, and M. Xue, 2008: A time-series weather radar simulator based on high-resolution atmospheric models. *J. Atmos. Ocean. Tech.*, **25,** 230-243.

*Dawson, D., 2009: Impacts of single- and multi-moment microphysics on numerical simulations of supercells and tornadoes of the 3 May 1999 Oklahoma tornado outbreak, School of Meteorology, University of Oklahoma, 173pp.
*Dawson, D. T., II, M. Xue, J. A. Milbrandt, and M. K. Yau, 2008: Improvements in the treatment of evaporation and melting in multi-moment versus single-moment bulk microphysics: results from numerical simulations of the 3 May 1999 Oklahoma tornadic storms. *24th Conf. Severe Local Storms*, Savannah, GA, Amer. Meteor. Soc., Paper 17B.4.
*Dawson, D. T., II, M. Xue, J. A. Milbrandt, and M. K. Yau, 2010: Comparison of evaporation and cold pool development between single-moment and multi-moment bulk microphysics schemes in idealized simulations of tornadic thunderstorms. *Mon. Wea. Rev.***,** In press.
*Dawson, D. T., II, M. Xue, J. A. Milbrandt, M. K. Yau, and G. Zhang, 2007: Impact of multi-moment microphysics and model resolution on predicted cold pool and reflectivity intensity and structures in the Oklahoma tornadic supercell storms of 3 May 1999. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred.*, Salt Lake City, Utah, Amer. Meteor. Soc., CDROM 10B.2.
*Gao, J. and M. Xue, 2008: An efficient dual-resolution approach for ensemble data assimilation and tests with assimilated Doppler radar data. *Mon. Wea. Rev.*, **136,** 945-963.
*Gao, J., K. Brewster, and M. Xue, 2006: A comparison of the radar ray path equations and approximations for use in radar data assimilation. *Adv. Atmos. Sci.,* **23,** 190-198.
*Gao, J., K. Brewster, and M. Xue, 2008: Variation of radio reflectivity with respect to moisture and temperature and influnce on radar ray path. *Adv. Atmos. Sci.*, **25,** 1098-1106.
*Ge, G., J. Gao, K. Brewster, and M. Xue, 2010: Impacts of beam broadening and earth curvature on 3D variational radar data assimilation with two Doppler radars. *J. Atmos. Ocean Tech.***,** Accepted.
Hong, S.-Y. and J.-O. J. Lim, 2006: The WRF single-moment 6-class microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, **42,** 129-151.
*Hu, M. and M. Xue, 2007a: Impact of configurations of rapid intermittent assimilation of WSR-88D radar data for the 8 May 2003 Oklahoma City tornadic thunderstorm case. *Mon. Wea. Rev.*, **135,** 507–525.
*Hu, M. and M. Xue, 2007b: Analysis and prediction of 8 May 2003 Oklahoma City tornadic thunderstorm and embedded tornado using ARPS with assimilation of WSR-88D radar data. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred.*, Salt Lake City, Utah, Amer. Meteor. Soc., CDROM 1B.4.
*Hu, M. and M. Xue, 2010: Analysis and prediction of 8 May 2003 Oklahoma City tornadic thunderstorm and embedded tornado using ARPS with assimilation of WSR-88D radar data. *Mon. Wea. Rev.***,** To be submitted.
*Hu, M., M. Xue, and K. Brewster, 2006a: 3DVAR and cloud analysis with WSR-88D level-II data for the prediction of Fort Worth tornadic thunderstorms. Part I: Cloud analysis and its impact. *Mon. Wea. Rev.*, **134,** 675-698.
*Hu, M., M. Xue, J. Gao, and K. Brewster, 2006b: 3DVAR and cloud analysis with WSR-88D level-II data for the prediction of Fort Worth tornadic thunderstorms. Part II: Impact of radial velocity analysis via 3DVAR. *Mon. Wea. Rev.*, **134,** 699-721.
*Jung, Y., G. Zhang, and M. Xue, 2008a: Assimilation of simulated polarimetric radar data for a convective storm using ensemble Kalman filter. Part I: Observation operators for reflectivity and polarimetric variables. *Mon. Wea. Rev.*, **136,** 2228-2245.

*Jung, Y., M. Xue, and G. Zhang, 2010a: Polarimetric radar signatures of a simulated supercell storm using a two-moment microphysics scheme and polarimetric radar emulator. *J. Appl. Meteor. Climatol.***,** Accepted.

*Jung, Y., M. Xue, and G. Zhang, 2010b: Simultaneous estimation of microphysical parameters and atmospheric state using simulated polarimetric radar data and ensemble Kalman filter in the presence of observation operator error. *Mon. Wea. Rev.***,** Accepted.

*Jung, Y., M. Xue, G. Zhang, and J. Straka, 2008b: Assimilation of simulated polarimetric radar data for a convective storm using ensemble Kalman filter. Part II: Impact of polarimetric data on storm analysis. *Mon. Wea. Rev.*, **136,** 2246-2260.

*Limpasuvan, V., D. L. Wu, M. J. Alexander, M. Hu, M. Xue, S. Pawson, and J. R. Perkins, 2007: Stratospheric gravity wave simulation over Greenland during 24 January 2005. *J. Geo. Res.*, **112,** D10115, doi:10.1029/2006JD007823.

*Liu, H., 2007: Analysis of GPS Slant-path Water Vapor Observations using 3DVAR with Anisotropic Filters and Their Impact on the Prediction of Convective Initiation and Precipitation, School of Meteorology, University of Oklahoma, 188pp.

*Liu, H. and M. Xue, 2006: Retrieval of moisture from slant-path water vapor observations of a hypothetical GPS network using a three-dimensional variational scheme with anisotropic background error. *Mon. Wea. Rev.*, **134,** 933–949.

*Liu, H. and M. Xue, 2008: Prediction of convective initiation and storm evolution on 12 June 2002 during IHOP. Part I: Control simulation and sensitivity experiments. *Mon. Wea. Rev.*, **136,** 2261-2283.

*Liu, H., M. Xue, R. J. Purser, and D. F. Parrish, 2007a: Retrieval of moisture from simulated GPS slant-path water vapor observations using 3DVAR with anisotropic recursive filters. *Mon. Wea. Rev.*, **135,** 1506–1521.

*Liu, S., M. Xue, and Q. Xu, 2007b: Using wavelet analysis to detect tornadoes from Doppler radar radial-velocity observations. *J. Atmos. Ocean Tech.*, **24,** 344-359.

*Martin, W. J. and A. Shapiro, 2005: Impact of radar tilt and ground clutter on wind measurements in clear air. *J. Atmos. Ocean. Tech.*, **22,** 649-663.

*Martin, W. J. and M. Xue, 2006: Initial condition sensitivity analysis of a mesoscale forecast using very-large ensembles. *Mon. Wea. Rev.*, **134,** 192–207.

*Martin, W. J. and A. Shapiro, 2007: Discrimination of bird and insect radar echoes in clear-air using high-resolution radars. *J. Atmos. and Oceanic Technol.*, **24,** 1215-1230.

*Martin, W. J. and M. Xue, 2007: Prediction of the timing of convective initiation along a dryline in a high-resolution model. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred.*, Salt Lake City, Utah, Amer. Meteor. Soc., CDROM 9B.6.

*Martin, W. J. and M. Xue, 2010a: Evolved and random perturbation methods for calculating model sensitivities and covariances. *Quart J. Roy. Met. Soc.***,** To be submitted.

*Martin, W. J. and M. Xue, 2010b: Determining sensitivities, impacts and covariances from very large ensembles with randomly perturbed initial conditions. *Quart J. Roy. Met. Soc.***,** To be submitted.

*May, R. M., M. I. Biggerstaff, and M. Xue, 2007: A Doppler radar emulator with an application to the detectability of tornadic signatures. *J. Atmos. Ocean Tech.*, **24,** 1973-1996.

Milbrandt, J. A. and M. K. Yau, 2005a: A multi-moment bulk microphysics parameterization. Part I: Aanlysis of the role of the spectral shape parameter. *J. Atmos. Sci.*, **62,** 3051-3064.

Milbrandt, J. A. and M. K. Yau, 2005b: A multi-moment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. *J. Atmos. Sci.*, **62,** 3065-3081.
Murphey, H. V., R. M. Wakimoto, C. Flamant, and D. E. Kingsmill, 2006: Dryline on 19 June 2002 during IHOP. Part I: Airborne Doppler and LEANDRE II analyses of the thin line structure and convection initiation. *Mon. Wea. Rev.*, **134,** 406-430.
Natenberg, E. J., 2008: Mutiple-Doppler radar analysis of a tornadic thunderstorm using a 3D variational data assimilation technique and ARPS model, School of Meteorology, University of Oklahoma, 127.
*Potvin, C. K., A. Shapiro, T.-Y. Yu, J. Gao, and M. Xue, 2009: Using a low-order model to detect and characterize tornadoes in multiple-Doppler radar data. *Mon. Wea. Rev.*, **137,** 1230-1249.
*Schenkman, A., M. Xue, A. Shapiro, K. Brewster, and J. Gao, 2010a: Impact of radar data assimilation on the analysis and prediction of the 8-9 May 2007 Oklahoma tornadic mesoscale convective system, Part II: Sub-storm-scale mesovortices on a 400 m Grid. *Mon. Wea. Rev.***,** Submitted.
*Schenkman, A., M. Xue, A. Shapiro, K. Brewster, and J. Gao, 2010b: Impact of radar data assimilation on the analysis and prediction of the 8-9 May 2007 Oklahoma tornadic mesoscale convective system, Part I: Mesoscale features on a 2 km grid. *Mon. Wea. Rev.***,** Submitted.
*Shapiro, A., C. K. Potvin, and J. Gao, 2009: Use of a mesoscale vertical vorticity in variational dual-Doppler wind analysis. *J. Atmos. Ocean Tech.***, 26**, 2089-2106.
*Sheng, C., S. Gao, and M. Xue, 2006: Short-term prediction of a heavy precipitation event by assimilating Chinese CINRAD radar reflectivity data using complex cloud analysis. *Meteo. Atmos. Phys.*, **94,** 167-183.
*Snook, N. and M. Xue, 2008: Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms. *Geophy. Res. Letters*, **35,** L24803, doi:10.1029/2008GL035866.
*Snook, N., M. Xue, and J. Jung, 2010a: Assimilation of CASA radar data for a tornadic convective system using ensemble Kalman filters. Part II: Ensemble Forecasting. *Mon. Wea. Rev.***,** To be submitted.
*Snook, N., M. Xue, and J. Jung, 2010b: Assimilation of CASA radar data for a tornadic convective system using ensemble Kalman filters. Part I: The EnKF data assimilation. *Mon. Wea. Rev.***,** To be submitted.
*Tanamachi, R. L., W. Feltz, and M. Xue, 2008: Observations and numerical simulation of upper boundary layer rapid drying and moistening events during the International H_2O Project (IHOP_2002). *Mon. Wea. Rev.*, **136,** 3106-3120.
*Tong, M., 2006: Ensemble Kalman filer assimilation of Doppler radar data for the initialization and prediction of convective storms, School of Meteorology, University of Oklahoma, 243pp.
*Tong, M. and M. Xue, 2005: Ensemble Kalman filter assimilation of Doppler radar data with a compressible nonhydrostatic model: OSS Experiments. *Mon. Wea. Rev.*, **133,** 1789-1807.
*Tong, M. and M. Xue, 2007: Investigating sources of inaccuracy in the analysis and forecast of a real tornadic thunderstorm case with the EnKF method through OSS experiments. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred.*, Salt Lake City, Utah, Amer. Meteor. Soc., CDROM 9B.4.

*Tong, M. and M. Xue, 2008a: Simultaneous estimation of microphysical parameters and atmospheric state with radar data and ensemble square-root Kalman filter. Part II: Parameter estimation experiments. *Mon. Wea. Rev.*, **136,** 1649–1668.

*Tong, M. and M. Xue, 2008b: Simultaneous estimation of microphysical parameters and atmospheric state with radar data and ensemble square-root Kalman filter. Part I: Sensitivity analysis and parameter identifiability. *Mon. Wea. Rev.*, **136,** 1630–1648.

*Wang, Q.-W. and M. Xue, 2010: A high-resolution modeling study of convective initiation on 19 June 2002 during IHOP. Part I: Control data assimilation experiment. *Mon. Wea. Rev.***,** Submitted.

*Xu, Q., S. Liu, and M. Xue, 2006: Background error covariance functions for vector wind analysis using Doppler radar radial-velocity observations. *Quart. J. Roy. Meteor. Soc.*, **132,** 2887-2904.

*Xu, Q., H. Lu, S. Gao, M. Xue, and M. Tong, 2008: Time-expanded sampling for ensemble Kalman filter: Assimilation experiments with simulated radar observations. *Mon. Wea. Rev.*, **136,** 2651-2667.

*Xue, M. and W. J. Martin, 2006a: A high-resolution modeling study of the 24 May 2002 case during IHOP. Part I: Numerical simulation and general evolution of the dryline and convection. *Mon. Wea. Rev.*, **134,** 149–171.

*Xue, M. and W. J. Martin, 2006b: A high-resolution modeling study of the 24 May 2002 case during IHOP. Part II: Horizontal convective rolls and convective initiation. *Mon. Wea. Rev.*, **134,** 172–191.

*Xue, M. and M. Hu, 2010: Tornadogenesis within the model-predicted 8 May 2003 Oklahoma City supercell storm. *Mon. Wea. Rev.***,** To be submitted.

*Xue, M. and H. Liu, 2010: Impact on convective initiation and precipitation forecast of simulated GPS slant-path water vapor data: Observing system simulation experiments. *Mon. Wea. Rev.***,** Under preparation.

*Xue, M. and Q.-W. Wang, 2010: A high-resolution modeling study of convective initiation on 19 June 2002 during IHOP. Part II: Localized forcing and convective initiation. *Mon. Wea. Rev.***,** Submitted.

*Xue, M., M. Tong, and K. K. Droegemeier, 2006: An OSSE framework based on the ensemble square-root Kalman filter for evaluating impact of data from radar networks on thunderstorm analysis and forecast. *J. Atmos. Ocean Tech.*, **23,** 46–66.

*Xue, M., K. K. Droegemeier, and D. Weber, 2007a: Numerical prediction of high-impact local weather: A driver for petascale computing. *Petascale Computing: Algorithms and Applications*, Taylor & Francis Group, LLC, 103-124.

*Xue, M., Y. Jung, and G. Zhang, 2007b: Error modeling of simulated reflectivity observations for ensemble Kalman filter data assimilation of convective storms. *Geophys. Res. Letters,* **34,** L10802, doi:10.1029/2007GL029945.

*Xue, M., M. Tong, and G. Zhang, 2009: Simultaneous state estimation and attenuation correction for thunderstorms with radar data using an ensemble Kalman filter: Tests with simulated data. *Q. J. Roy. Meteor. Soc.*, **135,** 1409-1423.

*Xue, M., J. Dong, and K. K. Droegemeier, 2010a: The analysis and impact of simulated high-resolution surface observations for convective storms with an ensemble Kalman filter. *Qart. J. Roy. Meteor. Soc.***,** To be submitted.

*Xue, M., Q.-W. Wang, and H. Liu, 2010b: Prediction of convective initiation and storm evolution on 12 June 2002 during IHOP. Part II: High-resolution simulation and mechanisms of convective initiation. *Mon. Wea. Rev.*, Submitted.

*Xue, M., Y. Jung, and G. Zhang, 2010c: State estimation of convective storms with a two-moment microphysics scheme and ensemble Kalman filter: Experiments with simulated radar data *Q. J. Roy. Meteor. Soc*, Conditionally accepted.

*Zhang, G., M. Xue, Q. Cao, and D. Dawson, 2008: Diagnosing the intercept parameter for exponential raindrop size distribution based on video disdrometer observations. *J. Appl. Meteor. Climatol.*, **47,** 2983-2992.