Major activities in the second year of the project were in the following areas

1. Mesoscale model simulations, verification and sensitivity to modeling of radar reflectivity
2. Evaluating the data assimilation approach using MCMC with 1D cloud resolving model
3. Graduate student training

1. Model simulations and verification with radar reflectivity observations

In order to develop an optimal approach to correcting deficiencies in bulk explicit parameterizations of precipitation processes in mesoscale forecasting by radar data assimilation, it is necessary to first evaluate model performance relative to radar observations and to diagnose model errors and an optimal measure of distance from these observations to use in the data assimilation. The study so far includes model verification on examples of IHOP (International H2O Project). In the first year we performed simulations of a sequence of storms during June 13 2002 in Central Great Plains. The simulations were performed with Advanced Research WRF (ARW, Skamarock et al. 2005; Wicker and Skamarock 2002; Michalakes et al. 1998) community model with 4-km horizontal grid spacing and 51 vertical levels and three available microphysics options. The results of verification of these simulations with observations including radar reflectivities using diagnostics such as histograms and 3D contingency tables in the radar reflectivity space indicate that the model forecast has extremely low skill relative to radar observations at point-by-point bases. For example, the 3D contingency tables in the binned reflectivities for 3 different microphysical parameterizations, have shown that the model does not agree with the observations at more than 90% of the points in 3D domain only few hours into the forecast, despite almost perfect agreement at the initial time. The agreement at the initial time results from initialization with LAPS analysis which includes observed reflectivities. This initialization provides "hot start" to the forecast. The "hot start" initial model data include cloud and precipitation hydrometeor fields with adjusted wind, humidity and temperature fields. In contrast to the point-vise diagnostics which show low forecast skill, comparison of 2D reflectivity horizontal cross-sections between the model and LAPS analysis indicated that the model captures some general features of the observed evolution of the storm system. The results of this analysis were presented at the 19th Conference on Numerical Weather Prediction in June of 2009. These initial results indicated that the model resolution should be increased for better comparison with the reflectivity observations.

In the second year of the project analysis and model simulations of two IHOP events have been performed using higher spatial resolution. The events occurred during June the 13-14 and 16-17 of 2002. The three different microphysical schemes were used as before, including Lin, WSM6 and Schultz. The model simulations were compared to gridded radar reflecitivty analyses that were produced by LAPS at the same spatial resolution as the model grid. To test sensitivity of verification diagnostics to the modeling of reflectivity from the forecast model background fields, we employed three different reflectivity models. These are commonly used empirically-based synthetic reflectivity calculations referred to as 'Kessler' and 'RAMS' and physically based radar model which includes options for different hydrometeor distribution parameters and careful modeling of radar measurement's geometry, designated SynPolRad . This radar model was developed at the DLR-Institute of Atmospheric Physics, Oberpfaffenhofen, Germany, by M. Pfeifer and collaborators (Pfeifer et al. , 2008) for studies in radar meteorology and for mesoscale forecast model validation. We have acquired the model from the developers by contact through Prof. Katja Frierdich of department of Atmospheric and Oceanic Sciences at CU, Boulder .

2. Evaluating the data assimilation approach using MCMC with 1D cloud resolving model

In the second year of the project Vukicevic co-authored on study and manuscript with D. Posselt of University of Michigan, entitled "Robust characterization of model physics uncertainty for simulations of deep moist convection (Posselt and Vukicevic, 2010. *J. Atmos. Sci, early on-line release*.). The study addresses properties of relationship between microphysics parameters and remote sensing observations in the context of data assimilation. The study abstract is as follows: *In this study, we seek to understand the functional relationship between model physics parameters and model output variables for the purpose of (1) characterizing the sensitivity of the simulation output to the model formulation and (2) understanding model uncertainty so that it can be properly accounted for in a data assimilation framework. We employ a Markov chain Monte Carlo algorithm to examine how changes in cloud microphysical parameters map to changes in output precipitation, liquid and ice water path, and radiative fluxes for an idealized deep convective squall line. Exploration of the joint PDF of parameters and model output state variables reveals a complex relationship between parameters and model output that changes dramatically as the system transitions from convective to stratiform. Persistent non-uniqueness* *in the parameter-state relationships is shown to be inherent in the construction of the cloud microphysical and radiation schemes, and cannot be mitigated by reducing observation uncertainty. The results reinforce the importance of including uncertainty in model configuration in ensemble prediction and in data assimilation, and indicate that data assimilation efforts that include parameter estimation would benefit from including additional constraints based on known physical relationships between model physics parameters in order to render a unique solution. Also the results suggest that using observations which are more directly sensitive to the microphysics such as radar observations should be beneficial to the results of data assimilation which include the effect of microphysics.*

Consistency of the results in this study with the known relationships between the cloud microphysical processes and with the relationship between the properties of remote sensing types of observations with respect to these processes, suggest that the 1D-cloud resolving model that was used in the study is suitable for further analysis of data assimilation approach for purpose of improving the microphysical parameterizations. Specifically, because the 1D model is already imbedded within very accurate and fully nonlinear data assimilation algorithm (MCMC - Markov Chain Monte Carlo) the analysis of the data assimilation results using the radar reflectivity observations with this modeling system would provide comprehensive evaluation of properties of the data assimilation solution with respect to the parameterized microphysical processes. Such evaluation would be infeasible with a 4D modeling system but is needed in order to understand constraints under which a feasible data assimilation algorithm should be applied, such as 4DVAR. For example, understanding of the conditions that would render a posterior pdf (probability density function) unimodal is highly desirable. These conditions are driven by the modeled relationship between the parameterized microphysical processes and by the observations of radar reflectivity including temporal resolution, length of assimilation window and quantities used to compute the cost function. The progression of the posterior pdf under variable conditions could be investigated only by analysis of the full pdf solutions as shown in Posselt and Vukicevic (210). Motivated by this approach, the new activity in the project in the second year involved implementation of the 1D model and MCMC algorithm at UM by graduate student van Lier-Walqui and diagnostic analysis of the microphysical processes in the model and simulation of the reflectivity from this model solution. The results are described in the summary of major findings. Graduate student training

3. Graduate student training

Marcus van Lier-Walqui transferred from ATOC at University of Colorado to RSMAS at University of Miami in Fall semester of 2009/10 academic year. He has been taking full load of graduate courses required by the graduate program and also 2 elective courses for the purpose of improving background knowledge and skills for the research project. The elective courses included methods for numerical modeling in atmospheric and oceanic sciences and statistical estimation.

Regarding training in the research project, Marcus acquired 1D lagrangian cloud model from Posselt and have implemented it successfully at a computer in RSMAS. He also developed interface between SimPolRad software and the 1D cloud model and have been testing two additional radar reflectivity models (SDSU , Satellite Data Simulator Unit, from NASA) and QuickBeam from CSU . These models are less computationally demanding than the SymPolRad while more sophisticated than the simple regression formulas such as Kessler and RAMS options that were used with WRF-ARW simulations in the first activity.

Prior report of Project Activities

Major activities in first 9 months of the project were in the following areas

4. Model simulations and verification
5. Using model verification results to define an optimal measure of distance between model and radar observations with respect to correcting bulk microphysical parameterizations by radar data assimilation
6. Learning WRF-4DVar data assimilation algorithm
7. Modeling of radar reflectivity
8. Graduate student training

4. Model simulations and verification

In order to develop an optimal approach to correcting deficiencies in bulk explicit parameterizations of precipitation processes in mesoscale forecasting by radar data assimilation, it is necessary to first evaluate model performance relative to radar observations and to diagnose model errors and an optimal measure of distance from these observations to use in the data assimilation. We start the study with model verification on examples of IHOP (International H2O Project) cases because of rich observational coverage during this observation campaign and readily available data archives. Besides, the IHOP cases provide diversity of summer storm systems to ensure robust diagnostic analysis for that type of system.

a) WRF model simulations

So far, we performed simulations of a sequence of storms during June 13 2002 in Central Great Plains. The simulations were performed with Advanced Research WRF (ARW, Skamarock et al. 2005; Wicker and Skamarock 2002; Michalakes et al. 1998) community model with 4-km horizontal grid spacing and 51 vertical levels and three available microphysics options. The three different microphysical schemes used were Lin, WSM6 and Schultz. The Lin scheme is based on Lin et al. (1983) and Rutledge and Hobbs (1984), with modifications for saturation adjustment (following Tao et al. 1989) and ice sedimentation. The WSM6 scheme is similar to the Lin scheme, with a different accretion calculation (Hong and Lim 2006). Time splitting is applied to the freezing and melting processes to increase accuracy in the vertical heating profile. The saturation adjustment follows Dudhia (1989) and Hong et al. (1998) in separately treating ice and water saturation processes. The exponential representation is used for graupel category for both schemes. The scheme of Schultz (1995) has been modified to use the saturation adjustment method of Asai (1965), to slow the melting rate of snow in air slightly warmer than freezing, and to allow for the formation of cloud liquid in unsaturated grid volumes with lapse rates approaching convective instability.

For each of the three microphysics configurations, non-local mixing Yonsei University (YSU) PBL scheme (Noh et al. 2003) – as an improved version of the Medium-range Forecast Model (MRF) PBL scheme (Troen and Mahrt 1986) – was used. The model runs were initialized at 00 UTC and run for six hours. Local Analysis and Prediction System (LAPS) diabatic initialization (Albers 1995, Albers et al 1996, Schultz and Albers 2003) was used for the model initialization. The LAPS diabatic initialization is based on a three-dimensional analysis of cloud attributes (*i. e.*, coverage, type and mixing ratios) that includes methods for estimating in-cloud vertical motions. By using a variational adjustment procedure (involving dynamic balancing and a mass conservation constraint; Smart and McGinley 2001), horizontal wind fields and the mass field are adjusted to produce divergence consistent with the specified cloud updraft properties (depth, magnitude, and shape of the updraft profiles). Essentially, the LAPS procedures enable the initialization of hydrometeors and balanced circulations driven by latent heating. This triggers an immediate activation of microphysical schemes and the development of grid-resolved precipitation at early forecast times of runs initialized with LAPS analyses. Global Modeling Forecast System (GFS) analyses and forecasts were used for lateral boundary conditions for all model runs.

b) Verification data from LAPS system

Evaluation of the model simulations was done by comparison of simulated 3-dimensional reflectivity to corresponding LAPS reflectivity analyses. Model forecast fields were converted into radar reflectivity using an empirical relationship between mixing ratio of modeled hydrometeors and radar reflectivity after Kessler (1969) and Rogers and Yau (1989). The verifying LAPS radar fields were generated as part of the cloud analysis package according to Albers et. al. (1996). WSR-88D full volume reflectivity data were mapped onto the LAPS grid using a polar-to-cartesian remapping program that operates on NetCDF files created using Level-II data from individual WSR-88D Doppler radars.

For each LAPS grid point, the remapping algorithm computes reflectivity by taking the mean Z value of all gates lying within a grid volume centered on the LAPS grid point. The use of all gates (rather than just the nearest neighbors) is advantageous in that it allows all of the radar information to influence the analysis and mitigates any noise that could be introduced by sub-sampling or spatial aliasing. The radar beam-width is assumed to be zero at this stage and only those grid volumes directly illuminated by the gates within the beam are filled in. We thus have the potential to produce a sparse array if the grid-resolution is < 10km or so. The average Z is converted to dBZ prior to output. When the mean reflectivity is less than a user adjustable QC threshold (e.g. 0 dBZ), it is set to a flag no echo value (e.g. -10 dBZ). If the data are nearly free of echoes, an output file is not written in order to save disk space. Another QC requirement is that at least 4 gates in the grid volume contain valid reflectivity data. This criterion is normally relaxed when the grid spacing is less than about 4km.

For high resolution grids, a post-process running within the remapper executable does horizontal filling between radials. This is currently a simple average of the nearest neighbors done only where gaps between radials are one grid-point across. The size of the filter kernel is adaptable as it is determined by the angular beam width (i.e. separation between successive radials, a run-time input parameter) and range from the radar. Since we often encounter gaps/holes covering only one grid-point (with 8 adjacent neighbors), this simple algorithm provides results largely equivalent to a Barnes weighting.

Vertical gaps in the reflectivity of up to 2 km are filled using linear interpolation. The gaps occur in the space between successive radar sweeps with increasing antenna elevation. The routine also has the option of filling in echo in low levels judged to be either below the radar horizon (due to the earth's curvature) or blanked out by mountains or ground clutter. Any echo whose base is within two LAPS grid levels (100 hPa) of the local terrain is assumed by the fill routine to extend down to the ground in reality. The 3-D mosaic is generated by considering the nearest radar to each LAPS grid point. This is advantageous since it avoids issues relating to movement of echoes if we wanted to use a weighted average of several of the nearest radars. A time window of +/- 600s is allowed for radar inclusion. Additional quality control is applied to the 3-D radar field within the LAPS cloud analysis. If the echo top is below 3000m AGL, or no pre-existing cloud-base is found (based on IR satellite and other data), no cloud is added and the radar echo is blanked out. Visible satellite is also used to flag false echoes. The cloud and precipitation analysis package can also operate with reduced capability using two-dimensional radar reflectivities, such as that provided by NOWRAD radar data over the continental United States. The low-level radar dataset is blended in a limited area that isn't covered by the full volume data.

c) Derived diagnostic data

Using the forecast and verifiying gridded reflectivity fields mentioned above several diagnostics were computed including, number of occurrences of binned values of reflectivity over the volume of the model domain that exceed a specified threshold (i.e. the histogram data), contingency tables and skill scores. The diagnostics were calculated for the simulated and observed fields for each model microphysics and each hourly output time step. Simulated vs observed contingency tables were calculated from the histogram data. The contingency table data were used to compute the skill scores. These include bias (ratio of simulated to observed number of points exceeding a reflectivity threshold) and Equitable Threat Score (ETS). To aid interpretation the histograms and contingency tables were visualized in several ways including 3-dimensional animations.

The standard LAPS algorithm was modified to compute these diagnostic quantities. This project data are now available via 'laps.noaa.gov' web site including all model forecasts, verifying analysis data as well as the observation and diagnostic data. The LAPS web site includes a separate sub-page for this project, through which the data can be visualized on-line using state of the art graphical display for the meteorological data (e.g., 2D figures of forecast and analysis fields, their differences and a set of standard derived diagnostic fields). The site could be reached via http://laps.noaa.gov, "On-the-fly Analyses/Forecasts". The project is under domain labeled NSF

5. Approach to defining an optimal distance to use in radar data assimilation with respect to errors in cloud microphysical parameterizations

Model evaluation by global diagnostics such as reflectivity histograms, 3D contingency tables and standard skill scores in the radar reflectivity space as well as comparison of 2D cross-sections of the reflectivity fields between the model and LAPS analysis show (next section) that the model forecast has very low skill relative to the observations on point-by-point bases. This result is expected and reflects among other factors presence of phase errors in the forecast. The phase errors are influenced by model dynamics and do not necessarily correlate directly with deficiencies in bulk microphysics parameterization, except through physics-dynamics feedbacks. In order to define a measure of distance between the modeled and observed radar reflectivities that would reflect primarily the impact of errors in modeling of the precipitation microphysics we designe the following analysis

Step 1 - 2D radar reflectivity fields from model and LAPS analysis are compared for each forecast output time (currently every 1 h) and each version of the model microphysics to identify sub-regions of corresponding coherent 2D reflectivity structures. We denote the sub-regions $S^i_{M\,j}(\tau_n)$ and $S^i_A(\tau_n)$ for the model and LAPS analysis, respectively; where i is the sub-region index, j is model version index ($j \in [1,3]$, for three different microphysical parameterizations used), and τ_n is time instance. The specific sub-regions for the modeled June 13 case were identified manually (by eye) and are discussed in the next section (Major findings). In the next phase of the project we will test using "automatic feature identification" approach (research in 2009).

Step 2 - For each sub-region the histograms of binned reflectivity values for each vertical level are computed

Step 3 - Normalized histograms are used to compute area average reflectivity per level and region in the following way

$$R^i_{M(A)_j}(\tau_n, l) = \sum_k r_k p_k \qquad (1)$$

where r_k is bin value and p_k is normalized count in the bin for each set (i, j, n, l); l is vertical index. Application of the expression (1) to the modeled and observed reflectivity would result in vertical profiles of horizontal weighted average of reflectivity from the model and observations.

Step 4 - L^2 norm distance between the modeled and observed reflectivities per level, model version and verification time could be then evaluated as follows

$$d_j^i(\tau_n,l) = \left[R^i_{M_j}(\tau_n,l) - R^i_{A_j}(\tau_n,l) - ^2\right] \qquad (2)$$

This procedure would result in a time sequence of vertical profiles of square differences of weighted average reflectivities within the equivalent coherent reflectivity structures. If these profiles are similar between different regions and times, then the distance function (2) could be employed as a measure of model error that primarily reflects systematic errors in vertical distribution of hydrometeor type and mass. Because the vertical distribution of the hydrometeor mass and type depends directly on the microphysical parameterization, this measure should correlate directly with the model errors in the parameterization. Also, sensitivity of the distance (2) to the model version (i.e., the microphysical parameterization) would indicate differences in errors from the different parameterizations.

Assuming validity of the condition in Step-4, the horizontally integrated reflectivity profiles by the expression (1) should be used to form cost function for the radar data assimilation with respect to correcting the microphysical parameterizations. We are currently evaluating the integral reflectivity profiles using the expression (1) and the associated distance function for the IHOP cases we are modeling.

6. Learning WRF-ARW-4DVar system

- Vukicevic and Jankov attended WRF-Var tutorial in July 2008 at NCAR. This tutorial included only 3DVar version of the WRF-Var system because this version is currently the public version. Because many components of the WRF-4DVar system are shared with the 3Dvar system, the tutorial provided useful instructions with respect to using the former.

- Vukicevic acquired WRF-4DVar algorithm from NCAR in Fall 2008, and received individual instruction on 4DVar components from collaborators at NCAR. An untested version of tangent linear and adjoint codes for the WSM6 microphysical parameterization was also acquired from the NCAR collaborators. Testing of this code will be done in Spring 2009.

- Vukicevic started code modifications in the 4DVar system regarding adding new control variables and cost function.

7. Modeling of radar reflectivity

The radar reflectivity model that is currently used to map the model hydrometeor data fields into the reflectivity space inside LAPS algorithm is based on empirical formula that is not representative of diversity of hydropmeteor particle distributions that are present across broad range of storm cases. Also, the radar data spatial mapping in the current analysis does not include geometry of the radar measurements . The accuracy of overall transformation of the forecast data into the reflectivity space for the purpose of computing distance between the model and observations may be significantly affected by errors in the physical and geometric mapping procedures. This could in turn affect the accuracy of data assimilation with the radar data.

To evaluate sensitivity of transformation of the model forecast to the radar reflectivity we plan to compare the current simple model results with state of the art physically based radar model which includes options for different hydrometeor distribution parameters and careful modeling of radar measurement's geometry. The model we plan to use is developed at the DLR-Institute of Atmospheric Physics, Oberpfaffenhofen, Germany, by M. Pfeifer and collaborators

(Pfeifer et al. , 2008) for studies in radar meteorology and for mesoscale forecast model validation. We have acquired the model from the developers by contact through Prof. Katja Frierdich of department of Atmospheric and Oceanic Sciences at CU, Boulder .

Marcus Van Lier-Walqui, the new graduate student supervised by Vukicevic at ATOC, who joined the current project in December 2009, will start implementation of the radar model by Pfeifer et al. in April 2009.

8. Graduate student training

Marcus Van Lier-Walqui, first year graduate student in ATOC joined the project in December 2008. Marcus has been trained in the following: a) acquire and visualize the project data from the LAPS analysis system; He already developed 3D visualization template using Matlab (example Figure 1 in section on Major findings), b) acquire and analyze observation data from the IHOP archive, c) perform literature search and summarize findings from publications and d) obtain major new software from outside sources (previous section).