## I. Introduction

It is necessary, for severe storm diagnosis and precipitation estimation over large domains, to combine radar data from several radars.

Merging radar data is a way to blend information from several radars, place it onto a common grid, and find the best estimate for a pixel based on the information from all of the radars that scan the interested area. The common grid used by Lakshmanan 2002 for the merged radar data was a lat-lon-height grid with uniform resolution in the three dimensions. The grids used in this study consisted of pixels with the dimensions of 0.01° longitude by 0.01° latitude by a height of 1-km (approximately 1-km by 1-km by 1-km). This was different from the polar grid of a Weather Surveillance Radar-Doppler 1998 (WSR-88D) which a pixel dimensions had the dimensions of 1° beam-for width by 1-km for gate-length with varying by 1° tilts for height. The 3-dimensional common lat-long-height grid was beneficial because other products such as 3-dimensional lightning data, satellite data, and model analysis can easily be placed on it (Zhang et al. 2002).

There were several different option methods for merging radar data – one can choose such as maximum reflectivity among all contributors to a voxel or, weight the contributors based on how far away from the radar data is, or weight them based on a time and distance metric (Lakshmanan 2002). By weighting far away pixels lower, we can account for the beam-spread and larger averaging area further away from the radar. For example, two WSR-88D's scanned one of the merged radar's pixels and one WSR-88D that was 60-km away gave a reading of 40dBZ 5-s ago while another WSR-88D that was 25-km away had four of its pixels land in the desired merged radar's pixel and gave readings of 40dBZ, 38dBZ, 37dBZ, and 35dBZ 15-s ago. What value should be assigned to the merged radar's pixel based on those readings? If maximum reflectivity was used then the value for the pixel would be 40dBZ because 40dBZ was the highest value from the two WSR-88D's for the desired pixel. However, the problem was this is an overestimate – the 40dBZ measurement might correspond to only a small part of the volume covered by the grid cell in the lat-lon-height grid. A value was entered into the merged radar's pixel, and if the radar data were not quality controlled, the maximum reading might be noise. If weight was added to the radar information based on how far it is from the WSR-88D, the value would be 37.65dBZ because the formula for the merged radar's pixel value was $\frac{(\Sigma w_i x_i)}{(\Sigma w_i)}$ and $x_i$ was the radar data and $w_i$ was the weight and equaled $\frac{1}{r^2}$ where r equaled the distance the radar data was from the WSR-88D (Lakshmanan 2002). If weight was added to the radar information based on how far it is from the WSR-88D and how much time has elapsed since the reading, then the value for the merged pixel would be 37.38dBZ because the formula for the merged radar's pixel value was $\frac{(\Sigma w_i x_i)}{(\Sigma w_i)}$ and $x_i$ was the radar data and $w_i$ was the weight and equaled $\frac{1}{(r^2 * t)}$ where t was the time elapsed since the radar reading and r was the distance the radar data is from the WSR-88D (Lakshmanan 2002). The main reason for choosing this method was it took both time and distance into consideration with merging, instead of just one variable. Also time-distance seems to be the most promising result, although there has not yet been a study on it.

The four cases included data from Oklahoma for: 9 October 2003 from 0000UTC to 1200UTC, 17 January 2004 from 0000UTC to 1200 UTC, 30 April from 0000UTC to 1200UTC, and 2 June 2004 to 3 June 2004 from 1800UTC to 0600 UTC. Reasons for choosing these cases are measurable amounts of precipitation fell throughout the 12-h period in the analyzed area. Furthermore, two cases, 9 October 2003 and 17 January 2004, had strataform precipitation while the other two cases, 30 April 2004 and 2 June to 3 June 2004, had convective precipitation. This gave the study a variety of precipitation types so that conclusions were not solely based on just one precipitation type.

The purpose of this study was to analyze the affect of adding quality control or quality control and advection to raw radar data before it was merged, and find the approach for merging radar with the least amount of error when compared to Oklahoma Mesonet precipitation readings. Because the Oklahoma Mesonet took precipitation readings every 5 minutes, precipitation rates were chosen for comparing the merged radar to the real-world readings. The next section in this paper includes what data and methods were used, the third section includes the results, and the fourth section is the conclusion.

## II. Methods

Mesonet , Ruc, and radar data were needed for this study. Radar data was collected from four WSR-88D's; Twin Lakes (KTLX), Fredrick (KFDR), Tulsa (KINX), and Enid (KVNX) were the chosen WSR-88D's because they are the main radars in Oklahoma, and Oklahoma Mesonet readings were needed to compare precipitation rates. Also Oklahoma was broken down into a large rectangle that had two corners in 39°N, 100°W and 34.5°N, 95°W. This prevented areas in Oklahoma that are not included in the range of the four WSR-88D's to be removed from the analysis, and it kept areas that were covered by more than one of the chosen radars in the analyzed area to be included.

The four radars were processed into three categories before being merged 1.) raw radar data, 2.) quality control added, and 3.) quality control and advection added. The the radar data was merged like it was real-time data coming into the computer with the time-distance method using the Warning Decision Support System – Integrated Information (WDSS-II) program on a Linux system. The main algorithms used in this program were ones for precipitation rates, merging, and quality control. More information on the WDSS-II and the algorithms used for this project can be found as of 29 July 2004?? at http://www.cimms.ou.edu/~lakshman/WDSS2/software/index.html.

After the radar data was merged, precipitation rates were found for the Oklahoma Mesonet stations and for the merged radar data. A Marshall-Palmer relationship was used to find the precipitation rates in which the rate can be calculated from the radar's reflectivity information (Marshall et al. 1948). This method was chosen because it is the default relationship on WSR-88D's and it was the method used by the National Weather Service (NWS). The formula used for this project was $R_r = (\frac{z}{a})^{(\frac{1}{b})}$ where $R_r$ was the rain rate in mm/hr , z was the reflectivity reading in dBZ, a=200 and b=1.6 when the precipitation was strataform, and a=300 and b=1.4 when the precipitation was convective(Marshal et al. 1948). The Ruc data aided in the decision of whether the precipitation was strataform or convective, this is discussed later in the paper. The Oklahoma Mesonet precipitation readings were time smoothed using a Kalman filter to prevent possible missed recordings that could cause error. The Kalman filter helps calculate values of time-dependent results from time-independent measurements (Hargrave 1989).

The Ruc data was needed to find the melting layer in clouds and to enter information into the hail detection algorithm. The melting layer was found by starting at the top of the cloud and moving down until the temperature was 0ºC. However, if there was an inversion there may be more than one layer, but this was the risk taken with this method. Then a simple filter would only accept reflectivity data that was at least 1-km below the melting layer. Also Ruc data was needed for the hail detection algorithm developed by Witt and other scientists. The algorithm detected the possibility of hail or severe hail and what might be the maximum size of the hail (Witt et al. 1998). If the hail detection algorithm noted that there was hail associated with the storm then the precipitation rates were set to convective precipitation and if there was no hail then the precipitation rates were set to strataform precipitation.

Quality control was added to the radar data by means of an automated algorithm developed by Lakshmanan and other scientists that uses a Neural Network. The algorithm looked at the differences of radar gates in a local neighborhood, including vertical and horizontal profiles, to determine if the radar echo was caused by precipitation or non-weather phenomena (Lakshmanan et al. 2003). Then it would remove non-precipitation echoes, such as anamalous propagation and ground clutter.

Advection was added to the radar data by means of liner extrapolation. The advection algorithm would move the radar echo horizontally based on how fast the echo was moving, what direction the echo was moving, how much time had elapsed, and whether the storm was decaying or strengthening (Lakshmanan et. al 2003).

After precipitation rates were calculated for both the merged radar data and for the Oklahoma Mesonet stations, a suitable way to compare each other was devised. A scoring program found the difference, or error, every five minutes during Oklahoma Mesonet station readings. The only cause of additional error is that the merged radar data does not coincide with Oklahoma Mesonet readings so the closet merged radar recording was chosen for error analysis. Also only pixels in the common grid with Oklahoma Mesonet stations were used to calculate error; the error was calculated by subtracting the Oklahoma Mesonet station's precipitation rate from the merged radar's precipitation rate.

Afterwards, there would be a total error for the five minute period by adding up each pixel with error.  In the end, all of the total errors were added up to get an accumulated error for the whole case.  In addition, the five minute total errors from each approach were graphed to see if there were any obvious patterns  <mention to look at a figure 1 here which is not made yet>.  Furthermore, the scoring program gave other statistics for the five minute error readings such as mean error, standard deviation, mean square error, and absolute mean error.  This information can be used in quantitative analysis.