Doppler Radar based Nowcasting of Cyclone Ogni

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Abstract

In this paper, we describe offline analysis of Indian Doppler radar data from Cyclone Ogni using a suite of radar algorithms as implemented on NEXRAD and advanced algorithms developed jointly by the National Severe Storms Laboratory (NSSL) and the University of Oklahoma. We demonstrate the applicability of the various algorithms to Indian radar data, the improvement in the quality of the data and evaluate the benefit of nowcasting capabilities in Indian conditions using this data. New information about the tropical cyclone structure, as derived from application of the algorithms is also discussed in this study.

Finally, we suggest improvements that could be made to the Indian data collection strategies, networking and realtime analysis. Since this is a first study of its kind to utilize doppler radar data in a tropical climate, the recommendations on realtime analysis and data collection strategies that we make, would in many cases, be beneficial to other countries embarking on Doppler radar network modernization programs.

1. Introduction

India is one of the most natural hazard-prone countries in the world, with floods, drought, landslides and cyclones being a regular threat to millions of its citizens every year. Most of the Indian landmass is prone to several natural disasters, with severe cyclones affecting the East and West coasts, large-scale flooding in the major river systems such as Ganges, Brahmaputra, landslides and earthquakes in the hilly tracts of Himalayas, and annual droughts affecting various parts of the country. Following two major disasters the Orissa cyclone in 1999 and the Gujarat earthquake in 2001, which together caused the death of more than 27,000 people and left more than 8 million
homeless. India renewed its focus on disaster management to protect lives and property. The need for better early warning systems and preparedness was again underscored with the tremendous loss of life caused by the tsunamis triggered by the Indian Ocean earthquake of December 26, 2004.

To address issues of disaster management, an Indo-US collaborative project for improvement and modernization of the hydrometeorological forecasting and early warning system in India was formulated as a part of the Government of India (GOI) USAID Disaster Management Support Project (DMSP). One component of this collaborative project has been the processing of Indian Doppler Weather Radar (DWR) data for nowcasting applications under the sub-project Local Severe Storms and Flash Floods. India Meteorological Department (IMD) and the National Severe Storms Laboratory (NSSL) have been working jointly in this direction.

a. Doppler Weather Radar Network Modernization

IMD has recently started upgrading its old analog radar network with a denser network of Doppler Weather radars (DWR). India Meteorological Department (IMD) has so far installed four S-Band Doppler Weather radars manufactured by GEMATRONIK Corporation (Model: METEOR 1500S) at Chennai(2002), Kolkata(2003), Machilipatnam(2004) & Visakhapatnam (2006) replacing the old generation S - Band cyclone detection radars at these stations. IMD has also installed one indigenous Doppler Weather Radar at Sriharikota in 2004. Figure 1 shows the current S-Band Doppler Weather Radar network in India. In addition to the current deployment of S-Band radars on the coast, there are plans to install more such radars inland (nearly 50 more radars) for utilization in severe storm forecasting and airport weather warnings. Radars play a key role in providing accurate estimates of severe weather systems with reasonable lead time for effective implementation of disaster warning systems.
In this paper we have analyzed the applicability of the single radar as well as multi radar algorithms of the Warning Decision Support System software (WDSS-II Lakshaman et al (2006)) to the radar data for the tropical cyclone Ogni obtained from the DWR at Chennai. The DWR at Machhilitpatnam too tracked the storm at the final stages. However this data was not of sufficiently high temporal and spatial resolution to provide much information about the structure of the cyclone or to be analyzed with the WDSS-II algorithms. The present study provides an indepth view of the structure of a tropical cyclone in this region of the world and makes a case for a improved disaster warning system for India for such severe weather phenomena utilizing the radar network.

b. *Cyclone Ogni*

In October 2006, the Andhra coast (eastern peninsular coast) of India was hit by a cyclone named Ogni. The size of the cyclone was so small (diameter 100 km) that operational synoptic weather charts and Numerical model outputs failed to capture the system till it was well on its way to becoming a cyclonic storm.

Cyclonic storm Ogni was first seen as a low pressure area over west-central Bay of Bengal off Andhra Pradesh coast in the morning of 28 October 2006. It intensified into a depression and lay centered near lat.14.0 N / long.80.5 E in the morning of 29 October 2006. While moving slowly in a northerly direction, it intensified into a deep depression and lay centred near 15.0 N / 80.5 E in the afternoon of the same day. The system further intensified into a cyclonic storm and moved slightly northward. Till the morning of 30 October, the movement of the system was very slow. Thereafter, it moved north-westward and crossed the Indian coast north of Chennai at Bapatla, as a deep depression around noon of October 30, 2006. Observationally it was a small core system.
and it attained cyclonic intensity for a few hours only. As a result of this system, there was heavy
to very heavy rainfall over north Tamil Nadu, Andhra Pradesh and south Orissa coast (55 cm over
Gudivada (16.43 N, 80.98 E) and 27 cm over Machilipatnam (16.12N, 81.08E) on 31 October),
during this period.

According to the cyclone report prepared by the forecasters at India Meteorological Depart-
ment, based on meteorological data from various sources, the cyclone was observed to have a
relatively narrow core in which the maximum wind sharply reduced to nominal values beyond
about 40 to 50 Km from the center. The wind speed over the eye-wall region at sea level was quite
strong although the aerial extent of high winds is relatively less. The half of the system closer
to the coast had lesser velocity probably due to frictional loading. Maximum reliable record of
wind speed is about 38 mps at levels between 3 to 4 km amsl (29 Oct/0618 UTC to 29 Oct/1218
UTC). Local print media reported incidents of fishermen (all along North Tamil Nadu and Andhra
Coast) experiencing heavy winds, with some of them missing during the period 29 October to 02
November.

Since the storm track was mostly parallel to the coast, it was well within the range of the
Doppler Weather radar at Chennai (13.01N, 80.268E) to track the evolution of the system from
Depression stage to Cyclonic intensity. Figure 2 illustrates the track of the cyclonic storm from the
depression stage to the point of landfall.

[Figure 2 about here.]

c. Organization

The rest of the paper is organized as follows. Section 2 describes the setup of the Doppler data for
offline analysis, and the set of analyses that were carried out on the data. Section 3 describes and
demonstrates the results from the analysis. Section 4 contains conclusions and recommendations – both regarding future organization of the Indian Doppler Weather Radar network and the state of NEXRAD radar data algorithms.

2. Method

The analysis was carried out offline on 72 hours of Doppler moment (equivalent to NEXRAD Level-II) data. As explained shortly, the data was subsected to form a synthetic Volume Coverage Pattern (VCP). The data were then analyzed using the Warning Decision Support System – Integration Information (WDSSII; Lakshaman et al (2006)), a suite of automated algorithms and display programs developed jointly by the National Severe Storms Laboratory and the University of Oklahoma. WDSS-II includes implementations of several severe storm analysis applications that are operational on the NEXRAD Open Radar Products Generator (ORPG), as well many next-generation algorithms. In this section, we will describe the analysis that was carried out on the Doppler data using both the algorithms currently operational in the United States and a more experimental set of algorithms.

a. Data setup

The Doppler weather radar data used in this analysis has a beamwidth of $1^\circ$ and provides 360 "beams" or radials of information per elevation angle. The area covered by one complete $360^\circ$ rotation at one elevation angle is called an elevation scan. The area covered by the radar beam as the antenna rotates through several elevation scans is known as a volume scan. The DWR radar at Chennai follows a series of different volume coverage patterns (VCPs) within a thirty minute
interval. The scans and their related parameters are listed in Table 1.

Utilization of the radar data in any automated analysis scheme such as WDSS-II requires predictability of the scanning strategy of the data at relatively short intervals. Algorithms based upon temporal aspects of pattern recognition will provide improved forecasts only when the data is of reasonably high quality (quality controlled), frequently updated in a predictable manner and scanning strategy is consistent. This is especially true for tropical convective storms in which cells have rapidly changing characteristics. Hence, the data flow (e.g., VCP update rate) must also be sufficiently high to capture the evolution of the phenomena of interest. However, as is clear from Table 1, some scans (e.g. the 11° scan) by the Chennai DWR are collected only once every 15 minutes. Therefore, they are not much use for incorporation into any automated analysis algorithm.

In view of the above problems, a synthetic VCP 301 has been subsected out of all the data available. This virtual volume has data at the same elevation angles as the 00 and 15 min. scans. However, in addition to the above two VCPs, we also extract the corresponding information from the 03 and 18 minute scans. In case a VCP misses a particular elevation, it is replicated from the previous scan for the same elevation. Since the elevation angles for the scan at 14 and 29 minutes are different from the rest of the VCPs, and does not contain data of enough volume around the radar to be of interest, this data is completely removed from the synthetic VCP 301. The bins per ray and the gatewidth for the synthetic VCP 301 are retained at 250 and 1.0 respectively. The data at 0.6 km bin slots was resampled to 1 km bins for the reflectivity field using a linear interpolation scheme and for the velocity and spectrum width fields using a nearest neighbour interpolation scheme. Hence the final VCP 301, as shown in the above table is available at 00, 03, 15, 18 minutes in every half an hour. The Pulse Repetion Frequency (PRF) for a particular tilt is used to
compute the Nyquist velocity for the velocity data of the corresponding scan.

A more extensive effort at creating virtual volumes from radar data with an unpredictable scanning strategy is currently underway at NSSL for data from phased array radars (Lakshaman and Hondl 2007). In that work, the range gates are treated as intelligent agents that place themselves in the resulting polar grid following interactions with other agents in the neighbourhood using different predetermined strategies. But in the case of radars without adaptive scanning and electronic beam control, as in the present scenario, it is better to be predictable in terms of the data collection.

The various WDSS-II algorithms were applied to the Indian Doppler radar data. Figure 3 displays the algorithms applied on the Indian radar data. The boxes indicate the WDSS-II algorithms. The grey boxes indicate the WSR-88D legacy algorithms that have been transported to the WDSS-II platform and implemented on the radar data. The dotted boxes indicate the QPESUMS algorithms that were applied on the data processed initially by the WDSS-II algorithms. Figures for the underlined products are displayed in the corresponding sections.

b. Dealiasing of velocity data

An operational challenge in using Doppler radar velocity field, is that velocity measurements are often aliased (folded). Aliasing occurs whenever the pulse repetition frequency (PRF) of the radar is lower than twice the Doppler frequency shift to be measured. Velocity aliases can usually be identified because true velocity fields must be continuous whereas aliasing causes unrealistic gradients (discontinuities) in the measured Doppler field.

The current Dealiasing technique for NEXRAD radars is the Local Environmental Dealiasing (LED) scheme of Eilts and Smith (1990). The algorithm looks for local 2-dimensional spatial and
temporal continuity of the velocity data field. An independent estimate of the true velocity in some areas is needed to initially start the procedure. This is obtained from upper air soundings. While this procedure is computationally quite efficient, this technique still has difficulties for cases with strong shear and small Nyquist velocities and in cases of large data voids. Besides, since the upper air soundings are usually very sparse in space and time, they are not representative of small-scale wind shears potentially leading to errors for whole sectors within velocity aliasing. Refer Figure 4 a and Figure 4 b for the application of the LED technique to the highly aliased field of this tropical cyclone. While Figure 4 a represents the original aliased velocity field for the tropical cyclone at 1648 UTC of 28 October 2006, Figure 4 b displays the velocity field for the same time, dealiased by the LED technique. The figure displays a highly aliased velocity field in the neighbourhood of the future center of the cyclonic storm. It may be noted from the figures above that there are large sectors of the velocity field that have not been dealiased properly by this technique, leading to a misrepresentation of the velocity field.

In this respect, a newer, 2-d (radial and azimuth) multiple pass technique was developed by Zhang and Wang (2006) to obtain more accurate and reliable reference velocities from radar velocity observations. The new technique eliminates the dependence on external data sources while facilitating a Dealiasing algorithm with high computational efficiency for operational implementation. This technique is also based on continuities in velocity field along radial and azimuth directions. Multiple passes of dealiasing and error checking are performed for robust dealiasing and also to improve the stability. This algorithm was found to successfully dealias most of the data in the present case. Refer Figure 4 c for the velocity field of the same time, dealiased by the above newer technique. The severe shear of the velocity field has been properly dealiased by the above
technique. This technique too sometimes gives errors, especially in case of low reflectivity, almost static echoes, but generally is able to dealias the velocity corresponding to higher reflectivity echoes which are of greater concern.

c. Quality control of reflectivity data

Weather radar data is subject to many contaminants, mainly due to non-precipitating targets and due to anomalous propagation or ground clutter. By removing the ground clutter contamination, estimates of rainfall from the radar data can be improved (Kessinger et al 2003) and false alarms prevented from the operational Mesocyclone Detection algorithm (Stumpf et al 1995).

In addition to the multiple VCPs, error in estimation of the evolution of a weather phenomenon may arise due to clutter in the radar data. The clutter in an image may arise from two main sources: (1) Ground Clutter Contamination (2) Anomalous Propagation. The vast difference in reflectivity images close to the radar, of near temporal origin, is not so much due to a change in the weather echoes over time as due to improper clutter removal by the radar manufacturer’s software. Normal ground clutter arises from unfiltered returns from stationary ground targets near the radar. These echoes are present only at the lowest elevations, close to the radar site and under most atmospheric conditions. Appropriate Clutter filter techniques have to be applied (as has been done in the present case to remove this type of clutter from the reflectivity scan images.

Other than the ground clutter as discussed above, the data has to be quality controlled to remove other non-weather echoes. The most significant is the error echoes due to Anomalous Propagation of the radar beams in the lowest elevations close to the ground. These echoes are produced during super-refractive conditions by ground clutter when the beam bends more than normal close to the ground. These echoes are generally radially oriented and there is transient clutter contamination
of scans. These echoes show wide reflectivity variations over large areas and lack uniformity or smooth reflectivity gradients. Observe for example, the reflectivity field at Figure 5 a at 0430 UTC of 28 October 2006. the anomalous propagation errors are clearly visible in the north east and southern sectors of the image.

This data can be quality controlled using just the radar moments and several techniques have been proposed to do this. Lakshaman et al (2003a) have developed a scheme that uses texture features as inputs to a neural network that can distinguish between precipitating and non-precipitating radar echoes. The neural network was trained on NEXRAD data using a million point dataset and was found capable of distinguishing most precipitation echoes from surrounding clutter. When these algorithms were applied on Indian Doppler Weather radar data, there were some specific situations where the texture features used as inputs to the neural network did not possess sufficient discrimination power. These situations include the presence of large, spatially smooth, clear-air returns. As may be observed from Figure 5 b , the neural network is able to remove most of the anomalous propagation errors. In addition, it also removes some of the spatially smooth, low reflectivity, clear air returns. The algorithm makes its mistakes on lower reflectivity values but gets higher reflectivity values (which are of concern during severe weather) correct more often.

[Figure 5 about here.]

d. Products derivable from the Dealiased Velocity data - estimation of Rotation and Divergence

The Azimuth Shear, which is the estimate of rotation in a storm, evaluates the derivative of the wind velocity in azimuth direction. In the present case, an algorithm has been applied that uses a two dimensional, Local Linear Least Squares Derivative (LLSD) method to minimize the large variances in rotational and divergent shear calculations (Smith et al 2004). There are several benefits
of using LLSD first derivative shear estimates. They are tolerant of the noisy data that is typical of radial velocity data. LLSD data are adaptable to various spatial scales. Besides the LLSD removes many of the radar dependencies involved in the detection of rotation and radial divergence (or radial convergence) signatures. Thus, these derivatives of the radial velocity field may be viewed in three-dimensional space or used as input to multisensor meteorological applications that require more than one radar as input. Additionally, fields of these radial estimates of rotation and divergence have specific signatures when boundaries or circulations are sampled. The Azimuth Shear and divergence signatures were found particularly useful in detecting developing cloud clusters, in areas of mesoscale cumulogenesis. In the present case Figure 7 displays the vertical structure of the Azimuth Shear in the region of a mesocyclone. The sharp change in the Azimuth shear in the lowest 2 km height is corroborated by the reflectivity maximum at the corresponding height.

e. **Storm Cell Tracking**

Severe weather algorithms are a key element of any weather forecasting mechanism. The original or legacy Severe Storms Analysis Program (SSAP) was the NSSL-developed algorithm system that operates on single-radar data and includes some of the severe weather algorithms that are now assimilated within the WDSS-II suite of algorithms. The SSAP components that have been integrated include the Storm-Cell Identification and Tracking (SCIT) algorithm, the cell-based Hail Detection Algorithm (HDA), and the Tornado Detection Algorithm (TDA).

The Storm Cell Identification and Tracking (SCIT) algorithm (Johnson et al. 1998) is a single radar algorithm and all algorithms and radar products are keyed to the individual volume scans and individual radars. The algorithm is based on a centroid identification and tracking technique and has been found more effective in tracking isolated cells. The SCIT algorithm processes volumet-
ric reflectivity information from radar base data on a radial-by-radial basis. The algorithm uses thresholds of reflectivity, length of segments, area of components (as well as other thresholds) and presence in at least two consecutive elevation angles to detect a storm. The centroids are then used as a proxy for the storms (Johnson et al. 1998) and tracked either on the basis of proximity to expected position or through a linear programming approach.

Prior to the organization of the cloud mass into a tropical cyclone, numerous small independent cloud clusters formed, gave rainfall and dissipated in the neighbourhood of the future storm center off the coast of Chennai. Figure 6a displays the reflectivity scan at the lowest elevation at a particular instant of time at 0518 UTC of 28 September, 2006. The SCIT cell tracker detects numerous cells at this instant of time. Position and past track (in pink) for seven cells is displayed in this particular figure. The parameters of all such cells identified in the current scan are displayed in tabular form. These include POSH (Probability Of Severe Hail), corresponding Hail Size, Vertically Integrated Liquid (VIL) in the cell, Height of Maximum Reflectivity (Z) as well as current location and probable direction of motion, and speed are listed. These cells are tracked through successive scans and their parameters are modified according to the intensification or decay characteristics of the cell or until their shape changes so much that they have to be identified again with a new cell identity. While the cells in these small clusters were quite well identified as well as tracked by the above algorithm, once the main system organized itself, the cells in the bands surrounding the system were not so well identified or tracked by the above algorithm. Also, since no velocity data are processed by this algorithm, the forecast performance is more accurate for short term forecasts than longer term forecasts.

[Figure 6 about here.]

With the development of communication networks and computer power, data from multiple
sensors (mesoscale models, satellite etc.) and multiple radars is available in near real time to forecasters and they have been the impetus to the development of a new generation of multi sensor severe storm analysis algorithms that provide better analysis and more accurate forecast for severe weather. The MR-SSAP (Stumpf et al 2002) combines the two-dimensional information from multiple radars and mosaics it into virtual volume scans (Lynn and Lakshmanan 2002), with the latest elevation scan of data replacing the one from a previous volume scan. This allows for a more complete 3-d sampling of storms and mesocyclones/TVSs where vertical sampling resolution is degraded. Signatures are better sampled where adjacent radars are adding data to poorly sampled regions such as cones-of-silence.

The only DWR close enough to the Chennai radar was the radar at Machilipatnam (16.12N, 81.08E). However, the radar data collected from the Machhilipatnam radar was at too low a temporal and spatial resolution to be combined with the data from the Chennai radar. However, in order to test the applicability of the multi-sensor and multi-radar algorithms to the Indian context, we created 3-d mosaics of the data from the Chennai radar alone, and applied the MR-SSAP algorithms to this data. Virtual volumes of radar data were constructed using the latest information from the Chennai radar for the previous 5 minutes. The Reflectivity information from these virtual volume scans is used to detect and diagnose storm cells in a lat-long grid unlike the first technique which was applied to resampled reflectivity data (in polar coordinates). In the present case, the performance of the SCIT algorithm within the MR-SSAP suite of algorithms at 0436 UTC of 28 October, 2006 at 1.5 km above ground is displayed in (Figure 6 b). The algorithm detects almost as many cells as the corresponding algorithm within the NETSSAP suite. However, in the absence of information from multiple radars, the temporal tracking of the cells is poorer from frame to frame.
f. **Mesocyclone Detection**

The basis of all mesocyclone detection algorithms is the automated pattern recognition of an area of rotation in the single Doppler radar radial velocity data. Since only the component of airflow directly towards or away from the radar is measured, areas of rotation appear as a couplet of strong localized opposing flows. The current Mesocyclone Detection Algorithm (MDA) (Stumpf et al 1998) follows a automated vortex detection technique to classify and diagnose a storm as a mesocyclone on the basis of 4-d properties of the storm. It also includes multiple range dependent strength thresholds, a robust 2-d feature identifier, an improved 3-d vertical association technique and addition of time association and trends to vortex attributes. The MDA attempts to detect all storm scale vortices and then diagnose them to determine if they are significant.

Tropical cyclones may spawn mesocyclones either ahead of, during or after landfall. However, since the shear in a tropical environment is relatively weak (Barnes 2001), especially in association with formation and maintenance of tropical cyclones, the mesocyclones thus formed, rarely attain sufficient strength to produce tornadoes. In the present case, some mesocyclones were identified north of the main system in the initial phase of formation of Ogni. These generally formed in the northwest, along the outer rainband of the developing cyclone system close to the zero velocity line. While most of these mesocyclones decayed within 10-15 minutes of their formation, a few of them lasted for more than 20 minutes and permitted a more indepth analysis of the characteristics of mesocyclones. Figure 7 a shows the location (close to the outer rainband of the developing cyclone system) and vertical structure of such a mesocyclone. The vertical structure of the reflectivity field in the neighbourhood of the mesocyclone is displayed in Figure 7 b while the horizontal shear field is displayed in Figure 7 c. The mesocyclone had a generally northward movement and the maximum intensity was observed to be 40 dB at 2 Km height and was tilted to the west, on the
landward side of the mesocyclone. The horizontal shear detected in this mesocyclone was comparable to those detected by Rao et al (2003) for the hurricane Floyd, and was observed to change sharply with height (from 0.002 to 0.002 s\(^{-1}\) over the lowest two km).

[Figure 7 about here.]

**g. Composite**

NSSL has developed the capability to merge multiple-radar data into four-dimensional (4D) grids (Zhang et al 2004; Lakshaman et al 2006). These grids are specified in latitude/longitude/height/time coordinate systems. Values in grid cells sensed by more than one radar are combined using a time and an inverse-distance weighting scheme. Terrain information is combined with beam power-density cross-sections to determine the amount of beam blockage. The data can be continuously updated each time an elevation scan from one of the radars is updated (every 10-20 seconds). It is possible to create 4D radar grids to cover a very large region using multiple radar grids. As already mentioned, the radar data collected from the Machilipatnam radar was at too low a temporal and spatial resolution to be combined with the data from the Chennai radar. However, in order to test the applicability of the above algorithms, gridded maps of maximum vertical reflectivity (sometimes known as Composite Reflectivity) and Vertically-Integrated Liquid (VIL) are constructed with Chennai radar data alone, with spatial resolution (1 km Cartesian grids) and updated every 5 minutes temporally. Figure 8 shows the reflectivity mosaic field at 0530 UTC of 28 October 2006, at 5km height constructed by the QPESUMS algorithm. The corresponding Vertical Integrated Liquid (VIL) is displayed in Figure 8. Other products include reflectivity at constant heights (CAPPIs), maximum reflectivity within any layer specified by two constant height levels, height of maximum reflectivity, maximum heights of constant reflectivity values (e.g., Echo Tops), and VIL.
Density (VIL divided by the depth of integration). However, the polar grid generally has higher resolution and is preferable unless the merger one can provide a larger spatial extent.

[Figure 8 about here.]

Having radar data on a lat/lon/height grid also makes it easier to combine with data from other sensors, particularly environmental data from a mesoscale model (e.g., 4.5 km WRF model output). The input of thermodynamic data is useful for deriving values of reflectivity at constant temperature levels (e.g., at the melting level of 0°C) and temperature layers, the height of constant reflectivity values above certain temperature levels (e.g., height of 50 dBZ level above the 0°C level), and the various hail diagnosis parameters.

**h. Forecast of echo growth and movement**

The centroid based identification and tracking of storms as discussed above in section can cause a number of tracking instabilities, especially with more organized systems. A newer, more sophisticated technique that uses a statistical clustering technique has been developed at NSSL to segregate and track multiple scales of reflectivity features to forecast the motion, growth, and decay of two-dimensional storm fields (Lakshaman et al. 2003b). The motion estimation application begins with a statistical K-Means clustering technique that can segregate multiple scales of reflectivity features in a hierarchical manner (larger clusters contain smaller clusters, and so on) and is done at three scales ranging from the tracking of individual cells to the tracking of large scale systems such as cyclones, which is more useful in this case. These clusters are tracked independently with greater stability than the centroid based algorithms. Time histories of tracked cluster can then be diagnosed for trend information. An additional benefit of the technique is the ability to incorporate
mesoscale model wind fields. This provides a more accurate estimation of the storm movement. The product also contains a storm growth and decay component.

This algorithm can be run on single radar data in polar coordinates as well as composite data from multiple radars. The results by both algorithms are comparable, but multi radar algorithm has the benefit of larger spatial coverage in the form of higher spatial extent. Since a tropical cyclone is not likely to show much identifiable movement in a span of sixty minutes, we concentrated on the growth component of the algorithm, which predicts the growth of the convective mass, for upto sixty minutes ahead. This component uses a linear prediction model. The figure below, is of the system, before it attained cyclonic storm intensity. While Figure 9 (a) displays the storm growth forecast sixty minutes ahead, for 0146 UTC of 29 October based on the data at 0046 UTC, Figure 9 (b) displays the storm growth forecast 30 minutes ahead for 0146 UTC based on the data at 0116 UTC, Figure 9 (c) displays the storm growth forecast 10 minutes ahead for 0146 UTC based on the data at 0136 UTC, while Figure 9 (d) displays the actual storm organization at 0146 UTC of 29 October. The forecasts have all been taken for the same time to illustrate the variation in the accuracy of the forecast with different lead times. As may be observed, the algorithm forecasts the growth of the system, much more quickly than the system actually does. The organization too is lost as the time of forecast increases. In this respect too, a model background wind field of a sufficiently high resolution, will contribute significantly to giving better forecast of the track and organization of the system.

[Figure 9 about here.]
i. Rainfall

The quality controlled mosaiced data from multiple radars is used to estimate the precipitation. This is essentially the NEXRAD precipitation algorithm with a better quality control technique and better convective/stratiform classification. From the 3-d grid, a 2D grid of reflectivity is estimated. In the 2D grid, the reflectivity at every point is given by the reflected power closest to the ground in the 3D grid. To prevent bright band contamination, the 2D grid does not get assigned reflectivity values if the value closest to the ground comes from a point higher than an estimated bright band height. The bright band is assumed to lie at 1 km below the zero degree isotherm. Precipitation rates are estimated in WDSS-II using a Marshall-Palmer Z-R relationship Marshall and Palmer (1948): $Z = aR^b$, where $R$ is the rain-rate in mm/hr, $Z$ is the radar reflectivity in dB and $a$ and $b$ are constants. The default settings recommended by Fulton et al (1998) were used: $a=200$ and $b=1.6$ in areas of stratiform rainfall and $a=300$ and $b=1.4$ in areas of convective activity. The presence or absence of hail as determined by the gridded HDA is used to discriminate between stratiform and convective precipitation. By means of groundtruthing studies, precipitation observed by gauges can be related to the corresponding radar estimate of rainfall at a point for a more rigorous calibration. However there are several potential or real sources of error in such comparisons: shadowing, anomalous propagation and ground clutter in the radar echo and uncertainty due to differences in the location of the sampled radar volume vs. the corresponding ground location, are some of the radar problems of precipitation measurement. Gauge observations are also subject to representativeness errors related to their siting and location, which means that the true relationship between radar-sampled precipitation and gauge precipitation observations will vary from station to station. Despite all these potential sources of error, data from four self-recording raingauges located at Tirupattur, Vellore, Madras and Pondicherry were chosen to
objectively validate the radar estimate of rainfall (Figure 10 a) obtained at 15-minute intervals. The
data is available at 15-minute intervals and data for the whole month of October 2005 was used for
validating the radar rainfall estimates.

The radar rainfall estimates accumulated for 15 minutes and for 60 minutes were checked
for the accuracy and bias in the estimate. Mean error, which is the difference between the radar
observation and the raingauge observation, measures the overall bias in the observation. A negative
value indicates the probabilities were too small on average; a positive value indicates that they
were too large. The mean error histograms computed for hourly rainfall accumulation, from radar
and SRRG, in Figure 10 b, demonstrate a negative bias in the data, indicating an underestimation
by the radar of the gauge rainfall. This error increases with the period of accumulation. The
Mean Standard Error was used to estimate the accuracy of the estimate (Figure 10 c). This too
demonstrates that the algorithm is relatively accurate for short period accumulations, but error
increases with the period of accumulation.

i. Rainfall estimation by the QPESUMS algorithm The QPESUMS algorithm was developed
at the NSSL and provides precipitation estimates for multi-hour precipitation accumulations using
sophisticated algorithms. This set of algorithms has been used with a great degree of success to
estimate rainfall from radar reflectivity data (Clarke et al. 2007). In the present case the com-
positing algorithm provides the 1 Km by 1 Km grids with 5 minute updates. The precipitation
rates are accumulated using hybrid-scan reflectivity fields to provide estimates of rainfall over the
past 1, 3, 6, 24 and 72 hrs. QPESUMS automatically integrates data from multiple sensors and
applies techniques to overcome deficiencies associated with the use of radar data such as terrain
blockages, limited coverage, beam geometry, bright band contamination, frozen hydrometeors and
errors in Z-R relationships. The QPESUMS comprises of numerous components including an au-
tomated removal non-meteorological radar artifacts through quality control (QC), application of
differential Z-R based on precipitation type and phase, delineation between bright band or frozen
precipitation and good radar sampling regions, application of satellite derived precipitation rates
and bias adjustment using hourly rain gauge data.

Figure 10 d and e displays the hourly accumulated rainfall by the two methods for the same
time. It may be observed that for the same dataset, the QPESUMS algorithm generally predicts
higher rainfall values and more detailed rainfall maps as compared to the precipitation algorithm
within the WDSS-II platform.

[Figure 10 about here.]

3. Results and Conclusions

The main objective of this study is to apply the WDSS-II and QPESUMS software of NSSL to
Indian DWR observations for nowcasting applications. In respect of the Ogni cyclone, this task
was successfully accomplished. Some recommendations and conclusions are listed as follows:

a. Employ predictable VCP

The Doppler weather radars installed in India are currently being used for nowcasting of both
mesoscale phenomena such as local thunderstorm events as well as large scale organized systems
such as monsoon depressions or tropical cyclones. In view of the operational and nowcasting
commitments, the radar stations had the following requirements:

• Creation of a rainfall input product - Surface Rainfall Intensity (SRI) based on 1km CAPPI
once every 15 minutes.

- Tracking of cyclones as they approach the coast.

- Tracking and detection of mesoscale systems including localized thunderstorms.

This was being done by performing a longer range scan and a SRI scan separately. The scans were being interwoven to obtain good velocity measurements. The three scans were repeated every 30 minutes.

On the other hand, for adequately utilizing the radar data to meet the nowcasting requirements, the scan strategy should have a long-range (500km) reflectivity scan, a high unambiguous velocity (at least 20 m/s), should be able to sample every location every 5 to 10 minutes and should have consistent spatial and temporal resolution.

However, on investigating the radar capabilities when trying to obtain above specifications, it was observed that the radar control software limits the speed, number of pulses etc. automatically to keep within the capabilities of the radar. At long Z, it was observed that the velocity data is poor (low Nyquist). Radar is not capable of good quality velocity data beyond 250 km. The antenna is also not capable of rotating at a speed of more than 18 deg/second. Further, it was observed that there are problems with the radar power-supply when high pulse repetition frequencies used.

By trial and error, we have discovered a way to implement a volume scan that accomplishes both goals. The Final scan was accomplished using a hybrid scan. It consists of a long-range (500 km) scan at low PRF for only Z, a shorter-range (250 km) scans at higher PRF for Z, V and sigma. The two were then combined within the Gematronik software using hybrid scan to create a SRI product.

The scan strategy was further fine-tuned to create two low-PRF scans so that vertical coverage is optimized. On this basis, two new strategies (created by Mr. Thampi, the director of the radar...
at Chennai and Shri Y.K. Reddy, Director of the radar at Machhilipatnam) are listed in Table 2 and Table 3. While the first scanning strategy was found applicable to short lived storms close to the radar, the latter scan strategy gave better results when the storms were longer lived and further away from the radar. The radar at Chennai was observed to hold both scan strategies without problem for long periods of time and has since been applied to all the Doppler Weather radars of Gematronik make in India.

[Table 2 about here.]

[Table 3 about here.]

b. Realtime Networking, data dissemination, tilt-by-tilt access

For any nowcasting application, the radar data should be transmitted to the data-processing machines in real time. The time-series data (Level I) is too voluminous to store/transmit. Hence there is a need to transmit radar moment data (Z, V, sigma: raw data) and further dissemination of raw data from a central location to interested users. Moreover, for more lead time in nowcasting applications, it should also be possible to access the tilt-by-tilt raw moment base data in real time. When data from various radars reaches a central location in real time, it is necessary to organize the data at station in time so as to queue the data in sequence of the time of their reception from various radar sites. This data from multiple radars can also be combined together at a central location to provide mosaiced data with large spatial coverage in earth projection, fused with NWP models, satellite data and data from other sensors, and delivered to interested users. Towards this end, a data manager (Possibly using open-source LDM software and 56K bandwidth line) may have to be used in the near future, to queue the data, as well as to redistribute it to various radar stations.
c. **Dissemination**

The raw data is assimilated into Numerical Weather Prediction (NWP) models, used for nowcasting, including incorporating satellite and NWP model data, rainfall analysis, including incorporating rain gauge and satellite data and for radar displays by media.

Regional nowcasting and analysis can be done at radar site. National nowcasting and analysis can be done at central facility. In addition to the use by meteorologists, decision making by various utilities, transportation and defence sectors requires raw radar data to derive customized threat estimates from various weather phenomena.

d. **Algorithms: India**

The WDSSII algorithms were applied to the Doppler radar data from one Indian radar at Chennai. Of the single radar algorithms, the newer multiple pass technique developed by Zhang and Wang (2006) successfully dealiased most of the highly folded velocity field, which the earlier Local Environmental Dealiasing (LED) scheme of Eilts and Smith (1990) was unable to detect. The neural network based quality control algorithm was also quite successful in detecting and removing the anomalous propagation echoes, in spite of being trained on NEXRAD radar data. It was, however, more successful in detecting the high reflectivity echoes, rather than the low reflectivity echoes from less intense convective cells. The SCIT and the MDA algorithms, (part of the legacy NETSSAP suite of algorithms) too detected and successfully tracked the storm cells quite well through successive scans. However, this algorithm was applicable only to data with 1 Km.
gatewidth. Hence higher resolution data at 0.6 km in the present case had to be downsampled to apply the algorithm leading to a loss of substantial amount of information. The Azimuth Shear and Divergence signatures were also found to be very useful, especially for locating the regions of development of new cumulus cells in mesoscale areas of convection. It was less of use for estimating the evolution of more large-scale organized systems, as in the present case for the main system.

While the single radar algorithms in polar coordinates were applied with a measurable degree of success, in the absence of collocated data from other DWRs with similar temporal and spatial resolution, the multiple radar algorithms did not generally provide any significant improvement in the nowcasting scenario. In many cases, the accuracy deteriorated, as in the case of the MRSSAP algorithm for storm cell detection and tracking. The forecast of the echo movement performed almost equally for both multisensor as well as single radar algorithms. The accuracy of estimate of the future intensity, position and organization in both instances was found to decrease significantly with the increase in the length of the forecast. Upto 30 minute forecast of echo movement and intensity was somewhat usable. Hence, these algorithms need to be trained and tested on a larger tropical dataset before it is usable in real time applications over India.

A significant source of error of the multisensor algorithms may be due to the default values used in the algorithms for the surface temperature, height of the freezing level and that of 100C and 200C. These default values correspond to the mid-latitudinal values of the temperature profile and are much lower than those for the tropics. Hence they presume the initiation of the cold cloud formation processes much earlier than in reality. Besides, the shear values in tropical barotropic regions, during formation of tropical cyclones is very low, as compared to a system in the extra tropics with similar vertical organization of reflectivity. This implies a much slower rate of growth for a cell in the tropics, than a similar cell in the midlatitudes. Hence, for more reliable operational
implementation of the WDSS-II algorithms to various climate regimes, the default thresholds for various parameters should be adjustable by the user concerned.

While it is not advisable to make lasting recommendations for the scan strategy as well as the WDSS-II algorithms on the basis of a single case study, the results discussed in this study are also consistent with other cases of local thunderstorms and synoptic systems, that have been studied using the data from this radar.

Acknowledgement The study was initiated as a part of collaboration work under the sub-project Local Severe Storm and Flash Floods of Climate Forecasting component of USAID Disaster Management Support Project. The first author is grateful to the government of India for kind approval of her deputation and to USAID /NOAA for funding the visit. The authors would like to thank Ms. Nina Minka of USAID, Dr. Robert Jubach and Ms. Carolyn Corvington of NOAA and Mr. Greg Austreng and Mr. N.M.Prusty and Mr.Balaji of USAID-IRG for constant support and cooperation at various stages to make the visit successful. Authors would like to thank AVMDr.Ajit Tyagi, DGM, India Meteorological Department and Shri R.C.Bhatia, ADGM for their encouragement, keen interest, valuable suggestions and providing all facilities to complete the work.

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Shri Hari Singh at India Meteorological Department for promptly and with extraordinary effort making the radar data available in the right format at a very short notice for this application and also cooperating fully in applying the new VCPs to the DWR stations.

References


## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
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<tr>
<td>1</td>
<td>The current S-Band Doppler Weather Radar network in India, with the rings indicating 400 km range.</td>
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<td>2</td>
<td>The track of the cyclonic storm from the depression stage to the point of landfall.</td>
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<td>Algorithms applied on the Indian radar data. The boxes indicate the WDSS-II algorithms. The grey boxes indicate the WSR-88D legacy algorithms that have been transported to the WDSS-II platform and implemented on the radar data. The dotted boxes indicate the QPESUMS algorithms that were applied on the data processed initially by the WDSS-II algorithms. Figures for the underlined products are displayed in the corresponding sections.</td>
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<td>(a) The original aliased velocity field for the tropical cyclone Ogni at 1648 UTC of 28 October 2006. (b) The velocity field for the same time, dealiased by LED technique. (c) The dealiased velocity field of the same time, dealiased by the newer technique of Zhang and Wang (2006).</td>
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<td>(a) Original reflectivity field at 0430 UTC of 28 October 2006 at 00.20 degree elevation. (b) The reflectivity field for the same time after the quality control algorithms have been applied.</td>
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<td>(a) Tracks and characteristics of storms detected by the single-radar storm cell algorithm of Johnson et al (1998). The track of past movement of the storms is displayed in pink lines. (b) Track and corresponding characteristics of some storms detected by the multi-radar storm cell algorithm.</td>
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(a) Location of the mesocyclone is close to the outer rainband of the developing cyclone system. (b) The vertical reflectivity structure (c) The vertical structure of the Horizontal Shear field in the neighbourhood of the mesocyclone.

Mosaic of the maximum vertical reflectivity (Composite Reflectivity) at 0530 UTC of 28 October 2006, at 5km height, constructed with Chennai radar data alone. On right: Vertically-Integrated Liquid (VIL) field derived from the 3D Mosaic using the methods of (Zhang et al. 2004; Lakshaman et al. 2006).

Radar reflectivity just before the system attained cyclonic storm intensity. While (a) displays the storm forecast 60 minutes ahead, (b) displays the storm forecast 30 minutes ahead for the same time, (c) displays the storm forecast 10 minutes ahead for the same time, while (d) displays actual storm structure at 0146 UTC of 29 October for which time all the above forecasts have been made.

Hourly accumulated rainfall by the (a) multi-sensor precipitation algorithm of (Clarke et al. 2007) (b) the multi-radar algorithm of (Lakshaman et al. 2006) (c) Location of four self-recording rain gauge stations located at Tirupattur, Vellore, Madras and Pondicherry used were chosen to objectively validate the radar estimate of rainfall. (d) Mean Error and (e) Mean Standard Error histograms for the 60 minute accumulated rainfall by the self recording rain gauge compared to radar accumulations for the same period.
Figure 1: The current S-Band Doppler Weather Radar network in India, with the rings indicating 400 km range.
Figure 2: The track of the cyclonic storm from the depression stage to the point of landfall.
Figure 3: Algorithms applied on the Indian radar data. The boxes indicate the WDSS-II algorithms. The grey boxes indicate the WSR-88D legacy algorithms that have been transported to the WDSS-II platform and implemented on the radar data. The dotted boxes indicate the QPESUMS algorithms that were applied on the data processed initially by the WDSS-II algorithms. Figures for the underlined products are displayed in the corresponding sections.
Figure 4: (a) The original aliased velocity field for the tropical cyclone Ogni at 1648 UTC of 28 October 2006. (b) The velocity field for the same time, dealiased by LED technique. (c) The dealiased velocity field of the same time, dealiased by the newer technique of Zhang and Wang (2006).
Figure 5: (a) Original reflectivity field at 0430 UTC of 28 October 2006 at 00.20 degree elevation. (b) The reflectivity field for the same time after the quality control algorithms have been applied.
Figure 6: (a) Tracks and characteristics of storms detected by the single-radar storm cell algorithm of Johnson et al (1998). The track of past movement of the storms is displayed in pink lines. (b) Track and corresponding characteristics of some storms detected by the multi-radar storm cell algorithm.
Figure 7: (a) Location of the mesocyclone is close to the outer rainband of the developing cyclone system. (b) The vertical reflectivity structure (c) The vertical structure of the Horizontal Shear field in the neighbourhood of the mesocyclone.
Figure 8: Mosaic of the maximum vertical reflectivity (Composite Reflectivity) at 0530 UTC of 28 October 2006, at 5km height, constructed with Chennai radar data alone. On right: Vertically-Integrated Liquid (VIL) field derived from the 3D Mosaic using the methods of (Zhang et al 2004; Lakshaman et al 2006).
Figure 9: Radar reflectivity just before the system attained cyclonic storm intensity. While (a) displays the storm forecast 60 minutes ahead, (b) displays the storm forecast 30 minutes ahead for the same time, (c) displays the storm forecast 10 minutes ahead for the same time, while (d) displays actual storm structure at 0146 UTC of 29 October for which time all the above forecasts have been made.
Figure 10: Hourly accumulated rainfall by the (a) multi-sensor precipitation algorithm of (Clarke et al. 2007) (b) the multi-radar algorithm of (Lakshaman et al. 2006) (c) Location of four self-recording raingauge stations located at Tirupattur, Vellore, Madras and Pondicherry used were chosen to objectively validate the radar estimate of rainfall. (d) Mean Error and (e) Mean Standard Error histograms for the 60 minute accumulated rainfall by the self recording raingauge compared to radar accumulations for the same period.
## List of Tables

1. Scanning strategy of the Chennai Doppler Weather Radar using Cyclone Ogni and the creation of a synthetic VCP from the scanning strategy actually followed. 42
2. Scanning strategy I for the Doppler Weather Radars operating in India. 43
3. Scanning strategy II for the Doppler Weather Radars operating in India. 44
### Table 1: Scanning strategy of the Chennai Doppler Weather Radar using Cyclone Ogni and the creation of a synthetic VCP from the scanning strategy actually followed.

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Table 2: Scanning strategy I for the Doppler Weather Radars operating in India.
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</tbody>
</table>

Table 3: Scanning strategy II for the Doppler Weather Radars operating in India.