Using the WSR-88D to Predict East Central Florida Waterspouts

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1.0 Introduction

The National Weather Service's (NWS) Modernization and Associated Restructuring (MAR) calls for the implementation of new equipment, the installation of new NWS offices, and an improved integration of operational and research meteorology. The ultimate goals are to ameliorate detection of hazardous weather features, increase warning lead-times, and improve overall service to the public. A cornerstone of the MAR is the installation of Weather Surveillance Radar - 1988 Doppler (WSR-88D) sites at existing and new offices and military bases across the country. When installation is complete, these radars will provide coverage for all the U.S. states and territories and their adjacent coastal waters.

In October 1991, the WSR-88D in Melbourne, Florida became the first radar positioned along a coast to become fully operational. Since then, meteorologists have observed many marine weather phenomena, one of which is the formation of waterspout and non-mesocyclone tornado producing cells near the coast. A review of archived radar products and detailed post analyses of seven of these events revealed similarities in formation, location, and progression of the associated cells (Choy and Spratt 1994). These similarities in radar signatures were combined with local spout climatology and knowledge from earlier work related to the synoptic and mesoscale precursor environments to formulate a system for anticipating the formation of these features in the east central Florida area. Using this technique, the potential for spout occurrence can be identified, general areas where formation is most likely can be predicted, and the public alerted before they form.

This paper introduces a climatology of spouts that occurred in the coastal area of east central Florida and discusses their possible formation processes. A forecast technique is presented which combines WSR-88D products with other available forecasting tools.

2.0 Coastal Spout Climatology

Griffiths' (1992) definition of the marine coastal environment was used to identify a local region for the spout study. Consistent with this definition, spouts which occurred within the area from twenty nautical miles inland, from the coast at the Flagler/Volusia County border to Jupiter Inlet on the Martin/Palm Beach County line, and within fifty nautical miles of shore were tabulated (Fig. 1). A climatology of the east central Florida coastal spouts was prepared using information from Storm Data (1973) and accounts from public reports. By reviewing meteorological conditions during each event, spouts were then separated from "classic" (supercell/mesocyclone) tornadoes. Based on

Figure 1. Map of east central Florida with the area of study outlined.

these reports the highest frequency of occurrence was centered around the Florida wet season from June through September (Fig. 2).

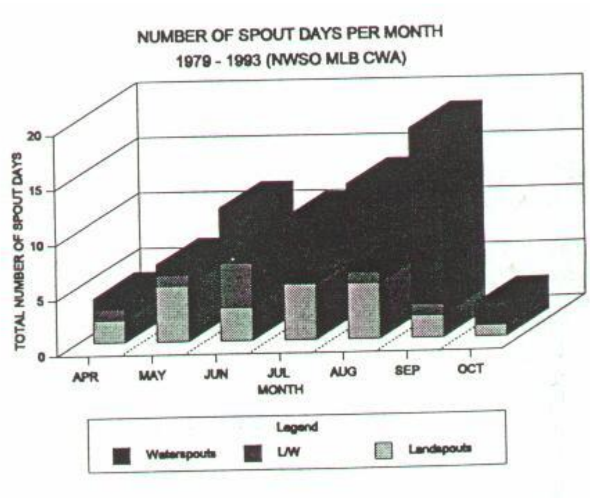

Figure 2. Number of Spout Days Per Month

It was noticed that more spout reports were received after the installation of the NWSO in Melbourne. Perhaps the presence of NWS personnel acted to encourage more spout reports, or the proximity of a local office offered an avenue for receipt of reports from the public. Spout reports from within this coastal area increased from an average of approximately 2 per year before the office's installation, to near 9 per year afterward. Within this region, the highest frequency of reports received centered around Cape Canaveral. Although the number of reports may be slightly higher in part due to a greater coastal population density and more marine traffic in the area, it is believed that the higher frequency was mainly due to local environmental factors.

3.0 Formation Process

The tornado formation process has been a subject of great study and intrigue for nearly a century. Today, it is widely accepted that tornadoes form within supercell thunderstorms (Browning 1964) where horizontal vorticity is tilted into the vertical and stretched by strong updrafts, producing a tornado (Klemp and Rotunno 1983; Klemp 1987). These supercell tornadoes can be persistent features which remain on the ground for an hour, or more on occasion. The surface vortex is a product of "spin down" from an intense mesocyclone which forms within the parent cell. These mesocyclones are typically large and intense with average diameters of 3-9 km and with differential velocities ranging from 40-80 m/s (Brady and Szoke 1988). This intense, larger scale rotation occurs about mid- level within the parent cell and usually extends through a deep layer, making them easily detectable by Doppler radar. Supercell storms form within baroclinic environments characterized by strong tropospheric winds/shear and large potential instabilities. Outbreaks of these storms have also been linked to the presence of synoptic-scale short-wave troughs.

With the exception of possible strong tornadic waterspouts associated with well-organized marine supercells (Hagemeyer 1994), waterspouts are generally rapidly developing and dissipating features of short duration; often lasting less than 20 minutes (Golden 1973). Most waterspouts have been observed to form along mesoscale surface air mass convergence boundaries. These boundaries are usually the product of other convective activity nearby or differential heating, but have also been observed to form and persist offshore in the absence of nearby convection or apparent strong surface temperature differences. In Florida, these boundaries have been detected with visible satellite imagery and radar, over the Atlantic and Gulf of Mexico waters. The horizontal wind shear and low level convergence along these boundaries act to produce cumulus congestus lines, and subsequent showers and thunderstorms. These cells occasionally spawn waterspouts.

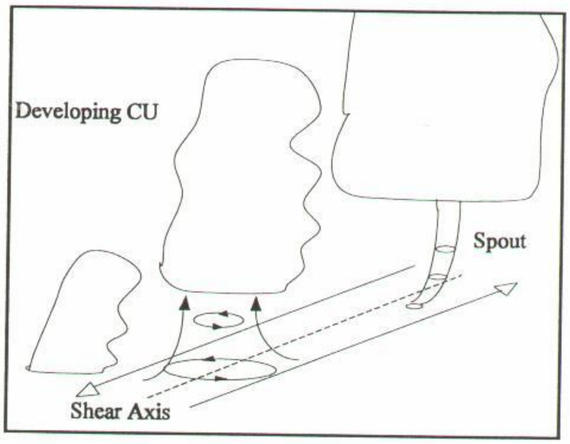

Figure 3. Formation of a waterspout due to updraft stretching of a low level vortex formed along a cyclonic shear axis.

It is believed that vortices are produced at or near the surface along the shear axis of these boundaries (Brady and Szoke 1988; Wakimoto and Wilson 1989). As these vortices propagate along the shear axis, they occasionally become collocated vertically with developing cumulus cells. The updrafts stretch the surface vortex, producing a spout (Fig. 3). A comparison between reported spouts and coincident WSR-88D data indicated that waterspouts are produced as cells are increasing in intensity (Choy and Spratt 1994). A similar observation was originally made in non-mesocylone tornadoes (landspouts) in Oklahoma (Burgess and Donaldson 1979) and appear to have a comparable precursor environment and formation process to waterspouts (Brady and Szoke 1988).

The complex formation process of non-mesocyclone tornadoes and waterspouts is still not fully understood. Perhaps there are several processes and mechanisms, besides the above mentioned "spin-up" process,, which could act to produce these features. Simpson et al. (1986) suggested that cumulus based vortices are necessary, but not sufficient in themselves to produce waterspouts. In modeled clouds, the addition of low level wind shear and lapse rate destablization acted to produce low level vorticity maxima ahead of an approaching gust front. Using rough vorticity tendency calculations, Simpson et al. (1986) further speculated that vortex stretching at the intersection of convergent features could act to strengthen cloud scale vortices to waterspout strength. These processes were more analogous to the "spin-down" process associated with supercell initiated tornadoes. Additionally, model results using environmental parameters from a Great Salt Lake waterspout suggested that under some circumstances, cumulus processes alone, without the addition of external vorticity from other sources such as shear axes and convergence lines, can produce waterspouts (Simpson et al. 1991).

It is well documented that waterspouts occur along, or near boundaries and their intersections (Golden and Sabones 1991). Golden (1974) observed that 95% of all waterspouts observed in the Florida Keys formed along a boundary. Additionally, waterspouts form in a quasi-barotropic environment characterized by weak tropospheric winds, with high humidity and warm surface water temperatures (Hess and Spillane 1992). From climatological studies it has been observed that areas with relatively large expanses of warm shallow waters along the coast also seem to favor waterspout development in east central Florida. Golden (1977) noted higher frequencies of waterspouts along the southeast U.S. and Gulf of Mexico coastline where bays, large intracoastal lagoons, and other warm shallow waters existed. In the Cape Canaveral area, the shape of the coast, combined with large intracoastal lagoons and numerous islands, act to produce boundaries and initiate convective cells through differential heating (Zhong and Takle 1993). Sea breezes north and south of the tip of Cape Canaveral often converge over these lagoons, providing the necessary boundaries, in coincidence with developing cells formed due to intricate differential heating. Waterspout formation in this area is most often observed after the onset of daily heating in the late morning through early evening hours.

4.0 Forecast Strategy

In the past, warnings and statements addressing waterspouts were usually written after a pubic report of an actively occurring waterspout. Statements and warnings normally then addressed the waterspout reported and mentioned the possibility of others to occur. This approach left the community largely unaware of a threatening spout.

Most waterspouts are relatively small; much weaker than land-based tornadoes, and move slowly, generally not posing much of a threat to mariners. These aspects, combined with their general inability to sustain themselves over land, make them less of a threat to the coastal community. However, a few spouts do form and/or move near or over coastal areas each year, causing considerable damage and a threat of casualties. The majority of these spouts occur on days uncharacteristic of severe weather and often unexpectedly. Therefore, a forecast strategy was developed to predict the formation of east central Florida spouts and possibly forewarn, or at least condition the public to possible occurrence, prior to formation. This approach requires the forecaster to recognize the spout precursor environment, focus on certain favored areas, and use WSR-88D and other forecast tools to detect boundaries and predict parent cell formation.

4.1 General Environment

Waterspouts have been observed to form in a variety of environments and synoptic regimes. It is impossible to account for every situation a waterspout can form under, but they can be effectively anticipated by categorizing the dominant factors associated with the majority of waterspouts. After reviewing the soundings and synoptic situations from spout days defined in section 2.0, it was observed that the majority of spouts occurred within a similar environment. The synoptic scale environment as mentioned in section 3.0 is characterized by light tropospheric winds in a quasi- barotropic environment and a moist low level air mass (mixing ratios 15-20 g/kg). In the mesoscale, warm surface water temperatures (25-31 deg C) in large shallow areas provide a nearly frictionless surface for broader vortex formation, while also providing a heat and moisture source. Boundaries in or propagating toward the preferred area from distant convective activity, should be closely followed since they can provide the low level shear, buoyant energy, and lapse rate destabilization conducive to waterspout formation.

It was noticed that waterspouts occurring outside of the Florida wet season predominantly formed in response to mid-latitude synoptic scale frontal intrusions in or near the area. The majority of these waterspouts occurred under favorable conditions near weak frontal troughs in April, May, late September, or October. The days with these conditions were easily identifiable because they are rare outside of the wet season. A few of these non-wet season waterspouts were stronger and longer lasting, with some of the parent thunderstorms containing supercell structure. These generally occurred within more baroclinic environments. Additionally, a few marine supercell storms were observed offshore which may have had strong tornadic-type waterspouts associated with them. Although some waterspouts form under highly sheared environments in association with marine supercells, these days are characteristic of severe thunderstorm development and easily recognizable. It is important to realize that these types of waterspouts can occasionally move onshore and pose a significant threat to life and property, such as the October 3, 1992 Tampa Bay outbreak (NOAA, 1993).

During the wet season, waterspouts formed in response to more mesoscale influences and localized differential heating effects. The following systematic approach focusses on wet season waterspouts, and will separate the most favorable days from those with a low probability of spout formation. It was developed for use in the east central Florida area.

4.2 Forecast Strategy - Step 1: Morning Sounding

The nearest sounding(s) in time and space should indicate winds within specific limits (Table 1).

TABLE 1

PRESSURE LEVEL	WIND SPEED
Surface - 975 mb	$\leq$ 4 ms^{-1} (8 kts)
974 - 700	$\leq$ 8 ms^{-1} (16 kts)
699 - 600	$\leq$ 10 ms^{-1} (20 kts)
599 - 500	$\leq$ 11 ms^{-1} (22 kts)

In addition to wind speeds within this range, a deep moist layer should be present from the surface to 500 mb, with Precipitable Water (PW) values of 1.7 inches or greater. The most useful tool in determination of spout potential is morning soundings in or near the forecast area (Fig. 4).

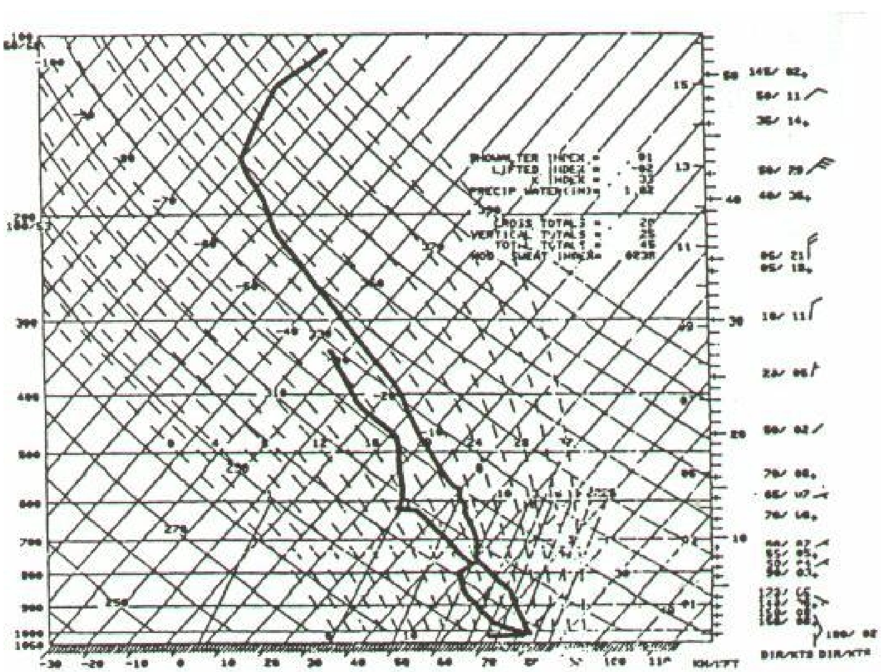

Figure 4. This July 22, 1994 sounding at 1100 UTC from Cape Canaveral is indicative of a high waterspout potential. Several waterspouts were reported along a boundary east of Cape Canaveral during the afternoon. Note the extremely weak tropospheric wind flow and plentiful moisture profile.

The sounding characteristic of a high spout potential is very pronounced. The most favorable conditions can be basically characterized by very light winds from the surface to the 500 mb level (often less than 5 m/s at all levels) and extremely high moisture (PW values 2.0+ inches). On rare occasions however, spouts have formed with winds exceeding the limits defined above.

The forecaster should look at other information in addition to soundings, especially if conditions are expected to change rapidly during the day. Model forecasts (NGM, ETA, AVN) should be reviewed on AFOS or PCGRIDDS.

Particular attention should be focused on winds within the lower half of the atmosphere and moisture advection toward or away from the area.

4.3 Forecast Strategy - Step 2: Boundary Detection

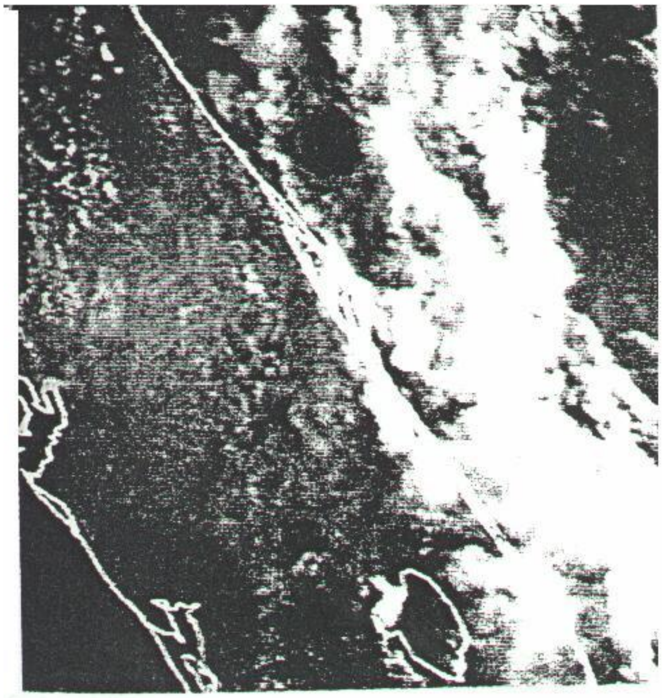

Figure 5. Several waterspouts were observed off of Cocoa Beach on July 22, 1994. This 1531 UTC GOES - 7 visible satellite image depicts cells which developed along an outflow boundary initiated by thunderstorms well offshore.

Waterspouts have occasionally been observed to form within individual cumuli and marine supercell storms. The overwhelming majority however, are associated with boundaries. Boundary detection is thus the key element in forecasting spout development, after environmental conditions have been determined favorable. Since the majority of waterspouts are observed to form along or near boundaries and intersections, the identification of these features using visible satellite imagery and radar will help identify possible locations for initial cell development, and subsequent waterspouts.

Using the WSR-88D, forecasters have noticed that boundaries are more easily seen by filtering the lowest Reflectivity (R) levels on the 0.5 deg R and/or CR products, and using the "combine-up" function (for information of WSR-88D products and abbreviations - see Crum and Alberty 1993; Klazura and Imy 1993). Boundaries should be especially suspect when approaching or converging in areas which are climatologically favored for spout development. Most of the spouts observed in the wet season formed with initial cell development occurring along a single boundary, such as a sea breeze front or outflow boundary from nearby activity (Fig. 5).

Waterspouts, some strong and long lasting, have also been noticed to form in association with rapidly developing cells between converging boundaries (Fig. 6). These are usually the product of two outflow boundaries colliding or an outflow boundary intersecting a sea breeze front. Interrogation of WSR-88D velocity products from the July 23, 1993 case revealed a broad area of relatively strong winds (>30 m/s) within the spout producing cell, but no apparent rotation (Choy and Spratt 1994).

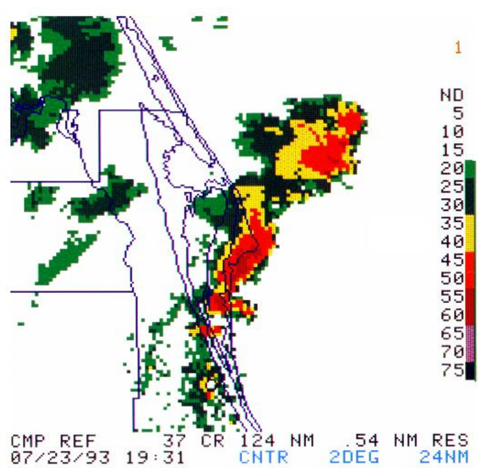

Figure 6. Composite Reflectivity 1931 UTC

4.4 Forecast Strategy - Step 3: Initial Cell Development

Waterspout prediction relies heavily on the ability to detect and anticipate initial cell development. Initial development must occur over or propagate toward water areas, especially across a preferred area. Along the east central Florida coast, the onset of a sea breeze in the late morning to early afternoon hours produces a sea breeze front just inland from the coast. Most of the shower and thunderstorm activity forms along this front. The additional vertical motion along the sea breeze front due to cell processes and additional heating act to produce a solenoidal flow along the coast with rising air inland and sinking air at the coast. Thus, a coastal subsidence zone sets up in response to the initiated sea breeze. This inhibits activity along and near the coast. When this is observed, waterspout formation will be unlikely over the coastal waters, even though the meteorological environment is favorable.

Given favorable conditions and development offshore, spouts will normally be observed to form during the early stages of these cells. At this point or sooner, a specific waterspout RPS list should be implemented to further interrogate possible spout producing cells (Spratt and Choy 1994). A RPS list was developed (Table 2) for use at NWSO Melbourne after examination of archived data from numerous spout events. The list contains may high resolution velocity products to help facilitate spout detection, in addition to other useful products.

LN	PROD NAME	DTA LVL	RES	SLICE	LN	PROD NAME	DTA LVL	RES	SLICE
1	R	16	.54	0.5	11	V	16	.27	0.5
2	R	16	.54	1.5	12	V	16	.54	0.5
3	R	16	.54	2.4	13	SW	16	.13	0.5
4	R	16	.54	3.4	14	SW	16	.13	1.5
5	R	16	.54	4.3	15	CR	16	.54	
6	R	16	.54	6.0	16	ET			
7	V	16	.13	0.5	17	VWP			
8	V	16	.13	1.5	18	SRM	16	.54	0.5
9	V	16	.13	2.4	19	SRM	16	.27	0.5
10	V	16	.13	3.4	20	VIL			

Table 2. WSR-88D Routine Product Set (RPS) list for waterspouts. See Spratt and Choy, 1994 for a detailed explanation of the usefulness of each product.

4.5 Forecast Strategy - Step 4: Statement

Given that the aforementioned criteria are met and the spout RPS or similar list is implemented, the focus of attention should shift to monitoring for rapidly developing cells. By tracking the progression of these cells along with determination of vertical development using Reflectivity Cross Sections (RCS's; through request or user function) and ET (Echo Top) products, the radar operator can focus on the rapidly developing trends in cells, especially those in or approaching the preferred area(s). If rapid development is indicated along or near boundaries and intersections in the preferred area, an enhanced short-term forecast (NOW) or Marine Weather Statement (MWS) should be prepared to alert the public to an area where spouts are likely in the near future. Click here to see an example of a actual statement recently written.

Several waterspout reports were received after the issuance of this statement.

4.6 Forecast Strategy - Step 5: Warning

After a statement is issued, the radar meteorologist should continue to interrogate developing cells for strong winds and/or rotation. Although it has only been noticed in a few of the east central Florida spout cases, largely after the spout was reported, organized rotation may be detected using high resolution V (Velocity) products. Golden (1974) noted through photogrammetry that the scale of rotation in Florida Keys waterspouts averaged 120 m, significantly less than the 250 m range by 1 degree of azimuth resolution of the highest V product. This product is also range limited. Additionally, the presumed "spin-up" formation process of these spouts would lead to rotation aloft at the time of or after formation of the spout, leaving no lead-time. This was true for all the cases involving rotation within east central Florida spout cells.

The SW (Spectrum Width) product has shown promise in funnel cloud and spout detection and may prove useful in the identification of spout producing cells. If an indication of strong winds or obvious strong rotation and high SW values are observed within a cell, or public reports are received, a Special Marine Warning (SMW) or a tornado warning (TOR) should be issued.

5.0 Discussion

The NWSO in Melbourne collaborates with NASA and hosts a sub- section in the Melbourne office which works closely with the Applied Meteorology Unit (AMU) at the Kennedy Space Center. Each day, a NWSO MLB forecaster is assigned to perform research associated with AMU projects. The waterspout strategy was implemented as part of the daily tasks for the Melbourne AMU forecaster during 1994. The waterspout potential was evaluated each day and statements and warnings were written based on the gathered information and forecast criteria. The basic synoptic criteria was observed on numerous days throughout the wet season. After assessing for favorable mesoscale radar signatures and preferred area criteria, the field narrowed considerably, resulting in the issuance of several MWS's addressing waterspout potential. During at least three occasions, waterspouts were sighted and reported after the issuance of a statement. On two occasions, a SMW was issued prior to a report of a waterspout. It was also noticed that forecasters continued to gain expertise after using the strategy and became more proficient at isolating very characteristic waterspout days from marginal days. Forecasters have also mentioned the possibility of waterspouts in the ATO (Area Thunderstorm Outlook) which is prepared during the morning hours, normally well before mesoscale influences are readily detectable or apparent.

It was noticed primarily at the onset of using this approach that there were many potential days and a greater care had to be taken when issuing statements. It is important that forecasters use great care when issuing these and any other statements, because they could have a considerable and possibly unwarranted impact on the community. As forecasters became more accustomed to the strategy and several waterspout events occurred in the area, the problem of overuse was largely self-corrected.

6.0 Summary

By using local spout climatology, synoptic charts, and soundings in the area, the forecaster can identify days with high spout potential. Combining knowledge of the areas mesoscale meteorology with recent radar and satellite images further allows the forecaster to pinpoint likely spout producing cells. By receiving a statement before the development of a spout, the public can avoid the area in a timely manner (sailing vessels are generally slow moving and require substantial lead time to avoid potentially severe weather). The statement also alerts the public to the possibility of spouts in the area and promotes rapid feedback should a spout form. Using the SW product may allow for better detection of spouts and funnel clouds. Future work should focus on this and high resolution V products so as to better locate spout producing cells. In contrast to analyzing WSR-88D velocity products during "classic" tornado development, reflectivity products appear more useful during wet season waterspout episodes. Boundary presence, and detection of cell initiation and rapidity of development have proven useful for better precursor indicators for spouts than velocity signatures.

The forecast strategy described in this paper was recently applied during daily operations at the Melbourne NWSO. The technique has been relatively successful for spout determination along the east central Florida coast. In addition to statements, information on the potential for waterspout occurrence has been mentioned in daily Area Thunderstorm Outlook (ATO) products. During several recent events, spouts were forecasted and statements and/or warnings were written prior to occurrence. There were still a number of spout- favorable days which did not produce spouts, apparently because development did not occur over the coastal waters. Future research will likely further refine this technique for the central Florida area. It is expected that forecasters in other coastal areas will find this technique, with minor modifications, useful for waterspout forecasting.

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