11B.5 THE IMPACT OF TROPICAL RAINFALL RATES ON FLASH FLOOD DETECTION

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) is responsible for the issuance of flash flood warnings to save lives and protect property. Most flash flood warnings issued by the NWS are based on the detection of heavy rainfall by the Weather Surveillance Radar, Doppler 1988 (WSR-88D). The capability of the WSR-88D to detect flash flood producing rain, typically rainfall rates of 25 to 200 mm hr^{-1}, is critical to the timely and accurate issuance of flash flood warnings.

If the WSR-88D indicates more rainfall than is actually occurring a warning may be issued where no flooding results. Rainfall overestimates tend to result from various forms of radar contamination including hail contamination, melting level contamination, ground clutter, and anomalous propagation. The "cry wolf" syndrome generated by such "false alarm" warnings is not helpful to the warning process.

A more dangerous scenario occurs if the WSR-88D underestimates the amount of rainfall that is occurring. If the WSR-88D fails to show the flash flood producing rainfall, a needed flash flood warning may not be issued. WSR-88D underestimation of rainfall can result from ground clutter suppression close to the radar (generally within 20 km), overshooting heavy rainfall at long ranges from the radar (greater than 150 km), beam blockage due to high terrain close to the radar, or warm rain processes requiring tropical rainfall rates. The impact of the warm rain process on flash flood detection will be the focus of this paper.

Rainfall can be produced by two distinct physical processes (Young 1993), the ice crystal mechanism (cold rain process) or by coalescence (warm rain process). The precipitation algorithm of the WSR-88D accounts for these two physical mechanisms by providing a choice of a standard convective rainfall rate (ice crystal mechanism), or a tropical convective rainfall rate (the coalescence mechanism). The radar operator must manually select which of these two rainfall rates will be used by the WSR-88D to estimate rainfall.

While the occurrence of tropical rainfall rates in tropical cyclones is expected, tropical rainfall rates can and do occur with thunderstorms not associated with tropical cyclones. The impact of the occurrence of tropical convective rainfall rates exclusive of tropical storms will be addressed in steps. The historical role of warm rain processes in flash floods will be discussed. The sounding parameters needed to anticipate the occurrence of warm rain processes will be detailed. The direct impact of warm rain processes on WSR-88D detection will then be summarized. The Shadyside, Ohio flash flood of 1990 will be presented as an example of the direct impact of tropical rainfall rates on flash flood detection. The comparison of rain gages with WSR-88D rainfall to verify tropical rainfall rates will be discussed in the context of the Johnstown, PA flash flood of 1977. Finally, a real-time comparison of WSR-88D rainfall with rain gage reports will be examined during the Homeworth, OH flash flood of 2003.

2. THE HISTORICAL SCOPE OF WARM RAIN FLASH FLOOD EVENTS

Heavy rain produced by tropical rainfall rates has resulted in some of the most devastating floods in the United States. The list of floods in Table 1 is compiled from two primary sources. The Automated Local Flood Warning Systems Handbook of the National Weather Service (http://www.nws.noaa.gov/oh/docs/alfws-handbook) and the National Oceanic and Atmospheric Administration (2001). The combined list of flooding events from these

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two sources is then cross checked with NWS Storm Data (National Climatic Data Center 1997) flood fatality statistics by month since 1960 to verify that major events were not excluded.

Table 1. Listing of twenty greatest monthly flood fatalities by state since 1960. Floods caused by: D = Dam Failure; F = Flash Flood Unknown Z/R; HI = Tropical Storm Inland Flooding; HS = Hurricane Storm Surge; S = Synoptic Storm; T = Flash Flooding due to Tropical Z/R.

Deaths	Year	State	Storm (Cause)
237	1972	SD	Rapid City (T)
153	1969	VA	Hurr. Camille (HI)
139	1976	CO	Big Thompson (T)
132	1969	MS	Hurr. Camille (HS)
125	1972	WV	Buffalo Creek (D)
78	1977	PA	Johnstown (T)
58	1969	CA	Southern CA (S)
58	1965	LA	Hurr. Betsy (HI)
56	1999	NC	Hurr. Floyd (HI)
51	1972	PA	Hurr. Agnes (HI)
40	1978	TX	TS Amelia (HI)
39	1977	GA	Tocca Falls (D)
38	1985	WV	Hurr. Juan (HI)
36	1961	TX	Hurr. Carla (HI)
36	1964	MT	Continental Divide (F) 350 mm of rain
36	1966	TX	Longview (F) 500-650 mm of rain
35	1994	GA	TS Alberto (HI)
30	1969	OH	Killbuck (F) 250-375mm in 15 hrs
28	1964	LA	Hurr. Betsy (HI)
26	1990	OH	Shadyside,OH (F)

Nine of the 20 worst floods, or 45%, resulted directly from inland flooding due to hurricanes and tropical storms. The Buffalo Creek, WV and Toccoa Falls, GA events resulted from dam failures, rather than flooding rainfall. One storm surge flooding event was due to Hurricane Camille along the Mississippi Coast. The January 1969 event in California was the result of a synoptic storm with orographic forcing of moist air over the mountains. These “pineapple express” events are driven by orographic lift of warm tropical air from the South Pacific and occur along the mountains of the west coast of the United States from November through March. The synoptic storm events are not flash floods caused by deep moist convection. The seven flash flood events that remain are flash floods that occurred as a result of deep moist convection, external to tropical storms or hurricanes. Four of the seven flash flood events can be directly classified as tropical rainfall rate events. Meteorological analysis of both the Big Thompson flood (Maddox et al. 1977) and the Rapid City flash flood (Maddox et al. 1978) have been documented as warm rain events. Direct evidence of warm rain processes will be presented later in this paper for both the Johnstown, PA flood of 1977 and the Shadyside, OH flash flood of 1990. Not enough information survives about the remaining three flash floods in the 1960s to make a valid determination of tropical rainfall rate occurrence, but a storm total of 20 to 26 inches in three days for the flash flood near Longview, TX in 1966 likely has some contribution from tropical rainfall rates.

Table 2. Selected tropical rainfall rate flash flood events 1972 to 2003, not associated with tropical storms. *Flash floods with the most fatalities in the continental United States for the calendar year.

Date	Location	Deaths
09June1972	Rapid City, SD	237*
31July1976	Big Thompson, CO	139*
20July1977	Johnstown, PA	78*
15August1980	Bradys Bend, PA	9*
13August1984	Hyndman, PA	5
14June1990	Shadyside, OH	26*
05May1995	Dallas, TX	17*
27June1995	Madison County, VA	3
19July1996	Brookville, PA	1
29July1997	Fort Collins, CO	5*
05October1998	Kansas City, MO	10*
28July2003	Homeworth, OH	0
31August2003	Kansas Turnpike	5

Flash floods caused by tropical rainfall rates are responsible for a large percentage of the worst flash flood events since 1960. For the 27-year period from 1972 to 1998, tropical rainfall rates produced the greatest number of flash flood fatalities in eight of those years, or at least 30 percent of the time. NWS storm data statistics show only six flooding events since 1960 have resulted in 75 or more fatalities. Two of the six resulted from Hurricane Camille with storm surge along the Mississippi Coast, followed by inland flooding in Virginia. One event resulted from dam failure in Buffalo Creek, West Virginia. The remaining three are all tropical rainfall rate flash flood events: Rapid City, ND; Big Thompson, CO; and Johnstown, PA.

It is not coincidental that many of the worst flash floods of the past forty years are the result of tropical rainfall rates. Davis (2001a) showed that when tropical rainfall rates occur that storm totals tend to increase rapidly and heavy rainfall tends to cover larger areas. Widespread heavy rainfall is a recipe for flash flood disaster. Slow moving hurricanes and tropical storms moving inland consistently provide widespread heavy rainfall. But tropical rainfall rates can and do occur exclusive of tropical cyclones. The occurrence of tropical rainfall rates can be the critical ingredient that tips the scales from a minor flood event to a flash flood of epic proportions.

3. ANTICIPATING THE OCCURRENCE OF TROPICAL RAINFALL RATES

The occurrence of tropical rainfall rates with tropical cyclones is well documented and can be easily anticipated, as land falling tropical cyclones are closely monitored by the National Hurricane Center for days in advance. The anticipation of tropical rainfall rates occurring exclusive of tropical cyclones is not so easily determined. The sounding parameters associated with warm rain processes have been well documented in Pontrelli et al. (1999) and Chappel (1993). Three factors of critical importance are a warm coalescence layer of 3-4 km or more, a deep layer of moisture as indicated by precipitable water values of at least 38 -50 cm, and dewpoints from 850 mb to the surface of 15^{o}C to 25^{o}C or more. These critical values may be a bit lower on the east slopes of the Rocky Mountains where surface elevations in such places as Fort Collins, CO and Rapid City, SD are close to 850 mb.

Davis (2001a) summarizes all the sounding parameters associated with warm rain processes including moderate values of CAPE (1500-2000 J kg^{-1}) preferable to extreme CAPE, because of the time needed for warm rain coalescence to occur. High values of CAPE, especially in the low levels of the storm, will rapidly accelerate the water vapor into the upper levels of the storm and limit the occurrence of coalescence (Young 1993).

Determination of tropical rainfall rate events prior to 1993 is difficult because of the unavailability of digital rainfall estimates before the WSR-88D installation. The Pittsburgh, PA NWS office had the Radar Data Processor (RADAP) installed in 1976. RADAP produced digital rainfall estimates using the Weather Surveillance Radar, 1957 (WSR-57) reflectivity. RADAP was the test bed for most of the WSR-88D severe weather and rainfall algorithms from 1972 to 1993. The availability of the RADAP rainfall estimates aided in the determination of the tropical rainfall rate events in Johnstown, PA, Bradys Bend, PA, Hyndman, PA, and Shadyside, OH.

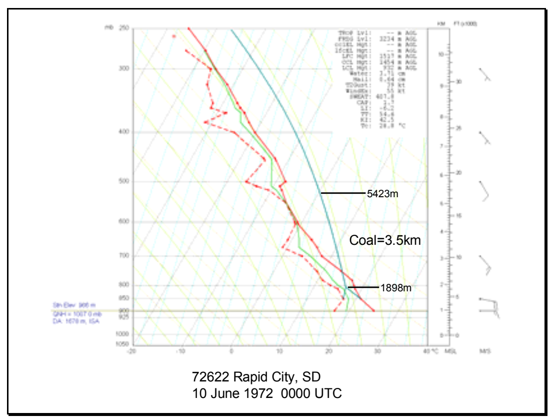

Fig. 1. Sounding analysis for Rapid City, SD on 10 June 1972 at 0000 UTC. Coal is the depth of the coalescence layer in km.

Figure 1 is the sounding analysis (all soundings created with RAOB program from Environmental Research Services, Matamoris, PA) for the Rapid City, SD flash flood of 1972. The warm rain coalescence layer (Coal) depth (km) is defined as the height (m) of the 0^{o} C parcel temperature minus the height (m) of the LCL in mean sea level (MSL). The LCL in MSL is the sum of the station elevation (m) plus the height of the LCL (m) above ground level (AGL). The

Coal depth in meters is divided by 1000 to convert Coal depth values to km.

Notice the deep layer of moist air as indicated by precipitable water (PW) of 3.71 cm (June normal PW 2.23 cm). The Coal depth is 3.5 km, well within the 3-4 km depth needed for warm rain processes.

In August of 1980 a severe flash flood struck the small Sugar Creek watershed at Bradys Bend, PA in Armstrong County. Satellite analysis of the event indicated that warm rain processes enhanced the heavy rainfall production (Schofield 1981). Figure 2 shows the sounding data for Pittsburgh, PA, 71 km southwest of Bradys Bend, PA. A deep layer of moist air is indicated by a

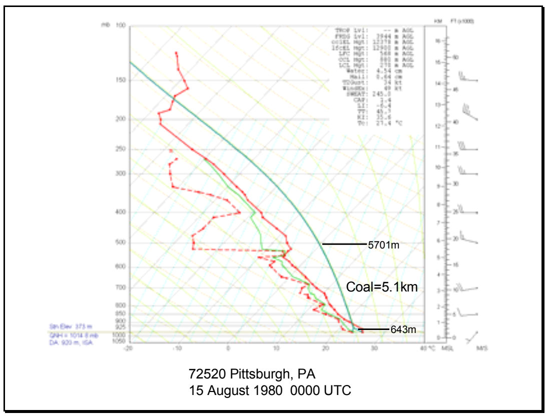

Fig. 2. Sounding analysis for Pittsburgh, PA on 15 August 1980 at 0000 UTC. Coal is the depth of the coalescence layer in km.

PW of 4.54 cm (August normal PW 2.60 cm). The Coal depth is over 5 km, well above the 3-4 km requirement for tropical rainfall rates. Rainfall started around 0000 UTC on 15 August 1980 and the thunderstorms became intense between 0100 and 0200 UTC on 15 August 1980. The bucket survey after the event could find no official rain gage reports, but one unofficial report had 126 mm of rain near Karns City, PA just west of the Sugar Creek watershed.

On 13 August 1984, 125 to 175 mm of rain fell between 1300 and 1600 UTC on the headwaters of Wills Creek in Somerset County, PA. The resulting flood wave killed two people in Glencoe, PA in Somerset County and three more people drowned in Hyndman, PA in Bedford County as the flood wave continued downstream. Almost no rain fell in Hyndman. The farmer who measured the 175 mm of rain indicated that no thunder and lightning occurred with the storm, but it was the heaviest rainfall he ever experienced. Figure 3 shows the sounding analysis from Pittsburgh, PA about 150 km northwest of Hyndman. A very deep layer of

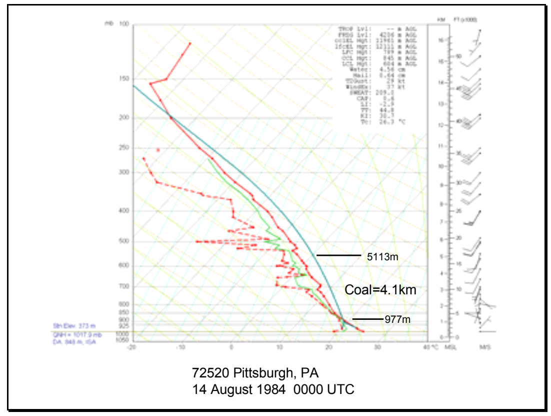

Fig. 3. Sounding analysis for Pittsburgh, PA on 14 August 1984 at 0000 UTC. Coal is the depth of the coalescence layer in km.

warm moist air existed as shown by the PW of 4.56 cm (August normal PW 2.60 cm). The Coal depth of over 4 km was on the high end of the 3-4 km needed for warm rain processes. The very narrow distribution of CAPE and lower equilibrium level may explain the lack of lightning. The Pittsburgh WSR-57 showed maximum radar tops of 6.7 to 7.6 km during the three hours of the heavy rainfall. RADAP rainfall estimates totaled only 40 mm for the storm using standard convective rainfall rates on RADAP. The headwater of Wills Creek above Hyndman is 130 to 150 km from the Pittsburgh WSR-57. The range from the radar may have contributed to the RADAP rainfall underestimation.

The Shadyside, OH flash flood of 1990 was one of the worst floods to occur within range of the Pittsburgh WSR-57 during its operational lifetime that ended in 1993. The fatalities during the Shadyside event occurred in three small watersheds, Pipe Creek, Wegee Creek, and Cumberland Run. These watersheds are 75 to 86 km southwest of the Pittsburgh WSR-57. Although the disaster survey team conducted a bucket survey, no rain gage reports were found in any of the impacted watersheds. A children's wading pool near the headwaters of Wegee Creek received about 125 mm of rainfall. Most of the rain fell in a 90-minute period. Section 5 will show a detailed summary of the RADAP rainfall estimates for the Shadyside storm.

The sounding analysis for this deadly warm rain event is show in Figure 4. A deep

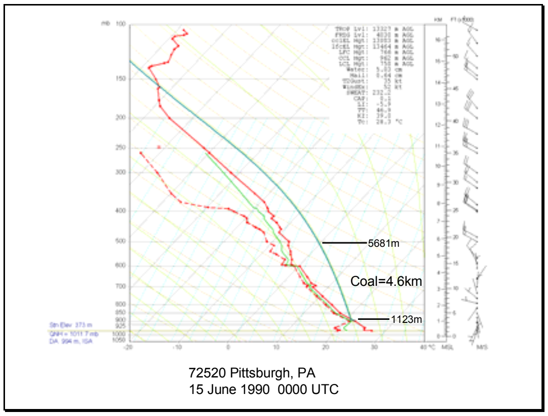

Fig. 4. Sounding analysis for Pittsburgh, PA on 15 June 1990 at 0000 UTC. Coal is the depth of the coalescence layer in km.

layer of warm moist air extends through 600 mb with PW of 5.03 cm (June monthly normal 2.40 cm). The Coal depth of 4.6 km is well above the needed 3-4 km threshold. Note the very light winds through the Coal depth allowing the storms to remain nearly stationary over a few small streams.

On 20 July 1977 a devastating flash flood struck the city of Johnstown, PA. The intense rain fell between 0000 UTC and 0800 UTC. Warm rain processes dominated through the storm, resulting in gross underestimates of RADAP rainfall. Section 6 will detail the comparison of RADAP rainfall estimates with rain gage measurements. The majority of the deaths occurred in three small watersheds: Laurel Run, Solomon Run, and Clapboard Run. These three small watersheds were between 107 and 120 km from the Pittsburgh WSR-57.

Figure 5 is the sounding analysis for Pittsburgh, PA, located 112 km west northwest of the city of Johnstown, PA. A deep layer of moisture is present through 600 mb with PW values of 4.91 cm (Monthly normal July PW 2.66 cm). The sounding is much more unstable than the previous four cases with larger values of CAPE. The Coal depth is 5.3 km, larger than the Coal depth of all other cases in Table 2. The wind

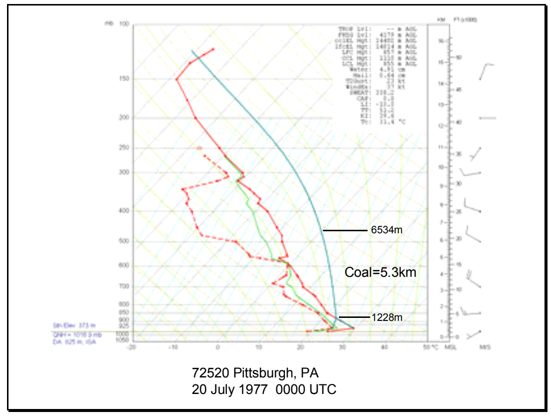

Fig. 5. Sounding analysis for Pittsburgh, PA on 20 July 1977 at 0000 UTC. Coal is the depth of the coalescence layer in km.

speed through the warm rain layer varies from 10 to 20 m sec^{-1}, considerably higher than the winds in the previous cases. There is little directional shear with west-northwest winds through the layer. The higher wind speeds spread heavy rainfall (200 to 400 mm in 8 hours) over several counties, resulting in widespread flooding.

These five tropical rainfall rate flash flood cases clearly show the importance of a deep layer of moisture, values of PW well over the seasonal normal, and a Coal depth of 3 km or more to support the occurrence of warm rain processes.

4. DETECTION OF TROPICAL RAINFALL RATES WITH THE WSR-88D

The occurrence of warm rain processes has three primary impacts on the radar detection of rainfall. First the vertical reflectivity structure is different for warm rain and cold rain processes. Second, the rainfall estimates produced by the precipitation algorithm will be very different when tropical convective rainfall rates are selected by the radar operator. And third, the vertical structure of the warm rain processes directly impact the effective hydrologic range of the WSR-88D. Recall the radar operator must select either standard convective rainfall or tropical convective rainfall for use by the precipitation algorithm. The purpose of this section is to show what factors must be taken into account to make that selection. Some case studies of tropical rainfall rate events are included to reinforce the sounding parameters of the previous section and show direct examples of WSR-88D detection of tropical rate flash flood events.

Unique vertical reflectivity signatures can be used to differentiate between warm rain processes or cold rain processes occurring within a storm. Warm rain processes result in vertical cross sections with high reflectivity values (40 to 55 dBZ) below the zero degree parcel temperature level (4.0 to 6.5 km in the cases in Table 2). When ice processes dominate rainfall production, high reflectivity often occurs well above the zero degree parcel level. In fact, reflectivity greater than 50 dBz above 7.6 km is often considered a threshold for the occurrence of severe weather (large hail or strong winds) in the summer severe weather season. Reflectivity greater than 60 dBz or higher at any level is most likely associated with hail or graupel, and therefore not associated with warm rainfall production. The vertical reflectivity cross section can aid in the determination of the real-time occurrence of warm rain processes, and the decision to use tropical rainfall rates on the WSR-88D.

The most obvious method to determine the occurrence of tropical rainfall rates is to compare WSR-88D rainfall estimates with real-time rain gage information. The Flash Flood Monitoring and Prediction (FFMP) program provides the capability to compare real-time rain gage information with the WSR-88D rainfall estimates for each rain gage in the NWS hydrologic database. The major limitation of this procedure is the limited availability of real-time rain gages. This methodology was used in real time for the Homeworth, OH case of Section 7.

The radar rainfall estimates produced by the WSR-88D are subject to significant range limitations. For standard convective rates the rainfall tends to be grossly underestimated at ranges beyond 150 km, as the radar beam overshoots the higher reflectivity occurring closer to the ground. When warm rain processes dominate in a storm, the higher reflectivity tends to be concentrated in the lower portions of the storm. As a result, gross underestimation of rainfall may occur beyond 120 km in range, when warm rain processes are operating.

The Areal Mean Basin Estimated Rainfall (AMBER) program, (Davis and Jendrowski 1996) was the basis for the FFMP software. The AMBER playback utility can be used to replay flooding event using tropical rainfall rates, or standard convective rainfall rates. The results produced by the AMBER playback will be a good approximation of FFMP real time rainfall estimates. Using AMBER playback, the author has replayed the flash flood events in Table 2 for: Dallas, TX; Fort Collins, CO; Kansas City, MO; and Brookville, PA to verify the occurrence of tropical rainfall rates.

The sounding analysis for these WSR-88D era cases are included to show the similarities with the pre-1993 flash flood cases (WSR-57) of the Section 3. Several of these WSR-88D era storms transitioned from standard convective rainfall rates to tropical rainfall rates. Some unique radar characteristics of each storm will be mentioned where appropriate.

Figure 6 shows the sounding analysis for the Dallas, TX storm of 1995. A severe bow echo moved across Fort Worth, TX and dumped large hail in the city. As the storm moved east into Dallas, the bow merged

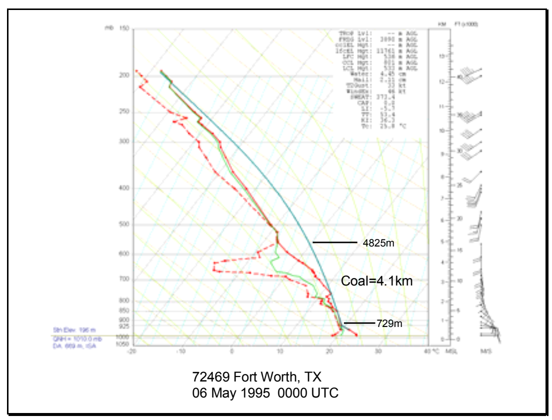

Fig. 6. Sounding analysis for Fort Worth, TX on 05 May 1995 at 0000 UTC. Coal is the depth of the coalescence layer in km.

with another cell and transitioned from a cold rain (hail producing) storm to a warm rain process event in a matter of minutes. The storm dumped torrential rain across the city of Dallas with over 100 mm of rain in one hour (Davis 2001a). The Forth Worth WSR-88D is 49 to 60 km from small streams in Dallas impacted by the flooding. Several of the Dallas mesonet rain gages reported over 50 mm of rain in 15 minutes. The dry intrusion on the sounding between 600 and 700 mb is not usually seen with tropical rainfall rates. The dry layer likely aided in the production of the large hail and may have been a transitory feature.

A severe flash flood struck the city of Fort Collins, CO on 29 July 1997. The Denver,

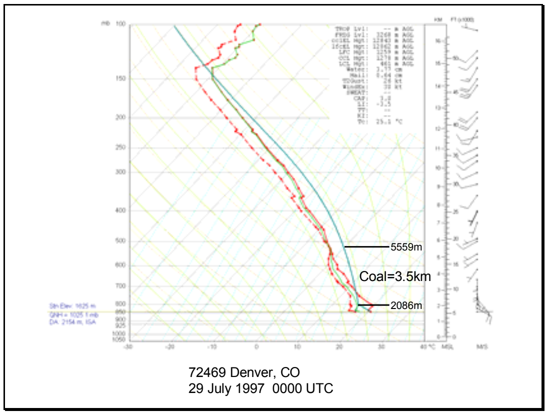

Fig. 7. Sounding analysis for Denver, CO on 29 July 1997 at 0000 UTC. Coal is the depth of the coalescence layer in km.

CO sounding analysis for the flood is shown in Fig. 7. Critical values of PW and Coal needed for warm rain processes should be lower for sites with higher surface elevations above sea level. The PW observed is 3.77 cm but the normal July PW for Fort Collins is only 1.86 cm. The sounding is very moist through the middle levels with a narrow distribution of CAPE. The storm over Fort Collins produced over 250 mm of rain in six hours (Davis 2001a). The Denver WSR-88D is 96 to 101 km southeast of the flooded Spring Creek watershed. The storm over Fort Collins showed classic warm rain characteristics with high reflectivity concentrated in the lowest levels of the storm. During an hour of some of the heaviest rain in Fort Collins, the Denver WSR-88D showed a strong thunderstorm northeast of Denver with radar reflectivity of 70 dBZ high into the storm. This storm well east of Fort Collins produced golf ball size hail as the heavy tropical rainfall was falling in Fort Collins.

The Brush Creek watershed in Kansas City, MO was the location of serious flash flooding on 13 September 1977 when 26 people lost their lives. A second flash flood occurred on the same Brush Creek basin on 05 October 1998 when 10 people drowned as their cars were swept off bridges in Kansas City (Davis 2001b). A NWS employee in Lenexa, KN (about 6 km west of Brush Creek) measured 127 mm of rain from 0010 UTC to 0125 UTC on 05 October 1998. The replay of the flash flood event using tropical rainfall rates showed a WSR-88D radar estimate of 128 mm for the Lenexa rain gage in the same 75 minute time period, verifying tropical rainfall rates.

Figure 8 shows the sounding analysis for Topeka, KN, about 90 km west southwest of Brush Creek. All of the soundings in this paper are unmodified soundings as measured by the NWS radiosonde site closest to the flash flood event. The sounding was launched about one hour prior to the onset of heavy rain in Kansas City. A warm deep layer of moisture is evident with a PW of 3.84 cm (October normal PW 1.77 cm) and Coal depth of almost 4 km. Both of these values were most likely higher over Brush Creek as the lower layers in the Topeka sounding have started to dry out as the showers moved east of Topeka. Increasing the low-level dewpoint will increase both the PW and the Coal depth.

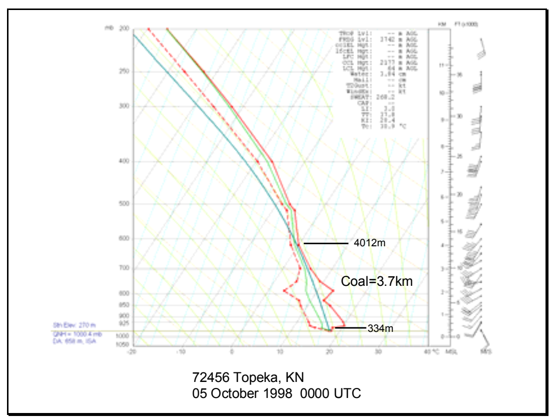

Fig. 8. Sounding analysis for Topeka, KN on 05 October 1998 at 0000 UTC. Coal is the depth of the coalescence layer in km.

The magnitude or severity of flash floods can not be measured directly by loss of life. Many flash floods occur in areas of relatively low population density where fewer people are at risk. The Madison County, VA flash flood of 1995 (Pontrelli et al. 1995) and the Redbank Creek flash flood of 1996 (Davis 2000) are both examples of severe flash flooding in rural areas of low population density. The efforts of local emergency management and rescue personnel with timely road closures and in-water rescues can be a big factor in reducing loss of life in even some of the worst flooding events. The NWS can greatly aid these rescue efforts by providing accurate and timely flash flood warnings to support the emergency operations.

Property damage in the Madison County event was staggering, with over 200 million dollars in damage. The storm total reached 600 mm of rain. Figure 9 shows the Washington Dulles sounding which is about 120 km east northeast of Madison County.

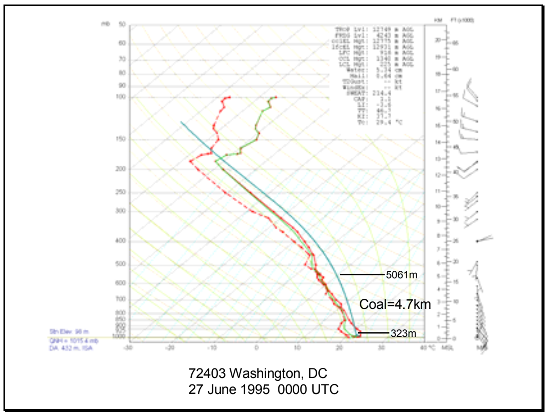

Fig. 9. Sounding analysis for Washington Dulles Airport, MD on 27 June 1995 at 0000 UTC. Coal is the depth of the coalescence layer in km.

The sounding is extremely moist with PW of 5.34 cm (normal June PW 2.70) with a Coal depth of almost 5 km. Note the very light winds through the Coal depth, allowing slow moving storms and huge rainfall amounts in small watersheds. The WSR-88D in Sterling, VA grossly underestimated the rainfall during this event due to both the tropical rainfall rates and the distance of Madison County from the radar.

The Redbank Creek flash flood resulted from heavy rainfall that fell from 0600 UTC to 1200 UTC on 19 July 1996. The training of thunderstorm trained across Venango, Clarion, and Jefferson Counties in PA for over six hours, dumping 100 to 200 mm of rain. The training speed of the storms averaged 25 m sec^{-1} through the six hours. Figure 10 shows storm total rainfall from the event for the Pittsburgh, PA (PBZ) WSR-88D using standard convective rainfall rates. Notice how the rainfall estimates appear to diminish in Jefferson County, as compared to Venango and Clarion Counties.

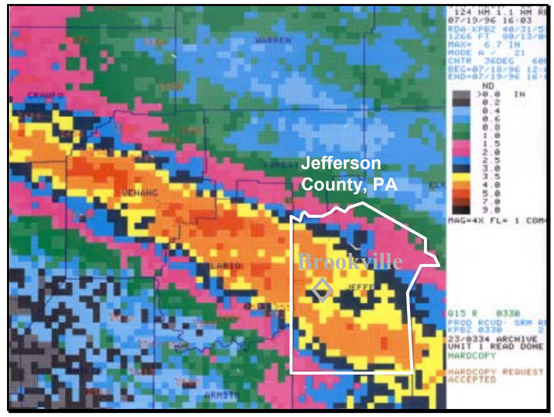

Fig. 10. Storm total rainfall for the Pittsburgh, PA (KPBZ WSR-88D) from 1200 UTC 18 July 1996 to 1600 UTC 19 July 1996. Rainfall in inches (1 inch = 25.4 mm)

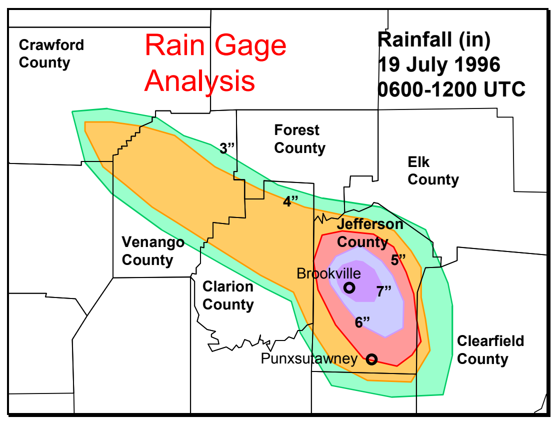

Fig. 11. Six hour rainfall from rain gage reports from 0600 UTC 19 July 1996 to 1200 UTC 19 July 1996. Rainfall in inches (1 inch = 25.4 mm)

The rain gage plot for the event (Fig. 11) clearly shows heavier rain in Jefferson County. Comparison of rain gages with radar rainfall in Venango and Clarion counties indicated standard convective rainfall rates were providing good radar estimates, but as the storms pushed east into Jefferson County the rainfall rates transitioned to tropical rates (Davis 2000).

The sounding analysis for the period of the heavy rain is represented by the Pittsburgh, PA soundings for 19 July 1990.

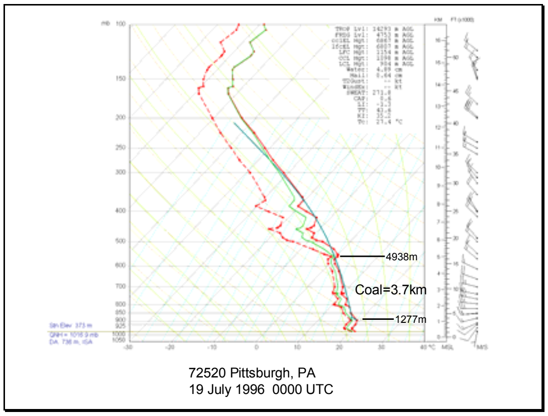

Fig. 12. Sounding analysis for Pittsburgh, PA on 19 July 1996 at 0000 UTC. Coal is the depth of the coalescence layer in km.

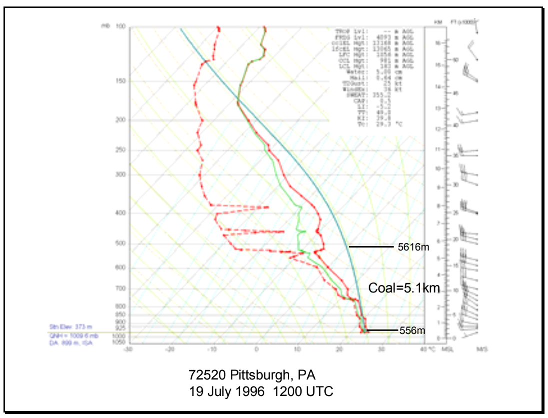

Fig. 13. Sounding analysis for Pittsburgh, PA on 19 July 1996 at 1200 UTC. Coal is the depth of the coalescence layer in km.

The Pittsburgh PA radiosonde site is 100 to 140 km southwest of the Redbank Creek watershed, but was representative of the warm southwest flow feeding moisture into the watershed. Figure 12 shows the 0000 UTC on 19 July 1996 sounding at Pittsburgh with a deep moist layer, PW of 4.89 cm (normal July PW 2.60 cm), and a Coal depth approaching 4.0 km. Note the increase in both PW (5.00 cm) and the big increase in Coal depth (5.1 km) on the 1200 UTC Pittsburgh sounding (Fig. 13).

5. THE DIRECT IMPACT OF TROPICAL RAINFALL RATES ON FLASH FLOOD DETECTION

The Shadyside, OH flash flood event will be used to demonstrate the direct impact of standard convective rainfall rates vs. tropical rainfall rates on the detection of flash flood occurrence. Exclusive of tropical storms, most NWS WSR-88D radars are set to use standard convective rainfall rates as the default. The FFMP program will display those computed rainfall rates and accumulations as Average Basin Rainfall (ABR) and ABR Rate for each defined stream segment (Davis 2003).

To simulate the FFMP graphic display of watersheds, RADAP data in twelve-minute time steps is used to compute the ABR and ABR Rate estimates for the FFMP defined watershed segments of Pipe Creek, Wegee Creek, and Cumberland Run. The ABR values for standard convective rate are plotted in Fig.14. Notice that Wegee Creek and Pipe Creek are each divided into 7 stream segments to improve flash flood detection (Davis et al. 2003), and Cumberland Run appears as a single watershed segment. Twenty-six fatalities occurred in these three small watersheds in a single horrific hour of flash flooding from 0130 UTC to 0230 UTC on 15 June 1990.

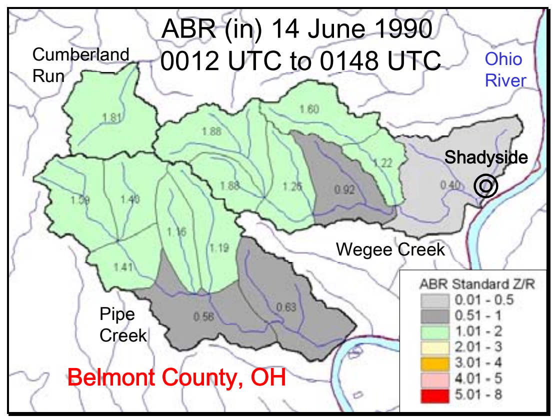

Fig. 14. FFMP ABR totals for streams near Shadyside, OH on 15 June 1990 from 0012 UTC to 0148 UTC using standard convective rates. Rainfall in inches (one inch equals 25.4 mm). Blue lines are stream channels and black lines are stream watershed boundaries.

FFMP compares the ABR with Flash Flood Guidance (FFG) to determine the possibility and potential severity of flash flooding (Davis 2002a). The “diff” column in the FFMP basin threat table is defined as the difference between ABR and FFG. Davis (2002b) has called this difference the FF-Index and shown how increasing values of FF-Index are directly related to flash flood severity. In eastern Ohio and western Pennsylvania values of FF-Index between zero and 0.5 inch are generally related to minor flooding problems, such as flooded basements or some ponding of water on roads. Index values of one inch or higher indicate significant flash flooding, while values of 2 inches or more are related to serious flash flooding, and 3 inches or more disastrous flooding results. The 1-hour FFG for Belmont County, OH was 1.30 inches. The FF-Index values in Fig. 15 indicate only minor flood potential, and only in the very headwater areas of Pipe and Wegee Creek. The areas shaded in green remain below the FFG values.

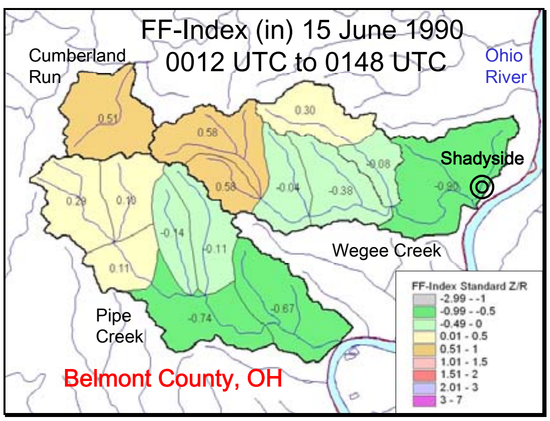

Fig. 15. The FF-Index (inches) for stream segments near Shadyside, OH for 15 June 1990 from 0012 to 0148 UTC using standard convective rates.

If warm rain processes are occurring in these watersheds, a very different picture takes shape as shown by the tropical rainfall rate version in Fig.16 and Fig. 17. The total accumulated ABR for the event using the tropical rainfall rate is shown in Fig. 16. The maximum ABR in the headwaters of Wegee Creek has gone from 1.88 inches (48 mm) to 4.05 inches (103 mm). The radar data is the same, the time period is the same, all that has changed is the rainfall rate from standard convective to tropical convective rates.

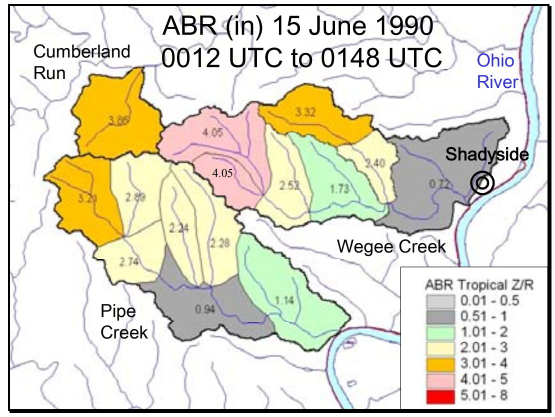

Fig. 16. FFMP ABR totals for streams near Shadyside, OH on 15 June 1990 from 0012 UTC to 0148 UTC using tropical convective rates. Rainfall in inches (one inch equals 25.4 mm). Blue lines are stream channels and black lines are stream watershed boundaries.

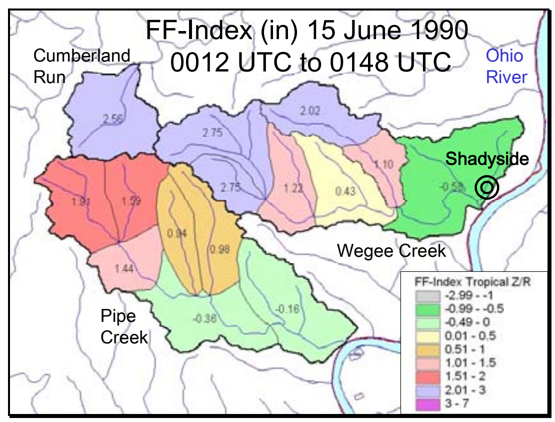

Fig. 17. The FF-Index (inches) for stream segments near Shadyside, OH for 15 June 1990 from 0012 to 0148 UTC for tropical rainfall rates.

The impact on the FF-Index, i.e. the actual threat of flash flooding, is also radically altered. Figure 17 shows the FF-Index computed using the tropical rainfall rates. Cumberland Run and the headwaters of Wegee Creek are more than 2 inches over FFG and indicating near disastrous levels of flash flooding possible. The difference between using standard convective rainfall rates and tropical rainfall rates can be the difference between issuing no warning, or issuing a warning for a very serious flash flood event.

In addition to impacting the warn/no-warn decision, tropical rainfall rate will also impact the amount of warning lead-time. The lead-time is the time from warning issuance to the time of the start of the significant flooding. A series of FF-Index plots in Figs 18-24 illustrate the on-going accumulation of heavy rain. A flash flood warning would likely be needed by the time the FF-Index turns positive (ABR greater than FFG) if rain continued to fall. Keep in mind that the RADAP data was only available in 12-minute time slices, while the WSR-88D data feed into FFMP using VCP 12 is now available in 4-minute time slices. At 0036 FFG has not yet been reached, but at 0048 UTC Cumberland Run has exceeded FFG.

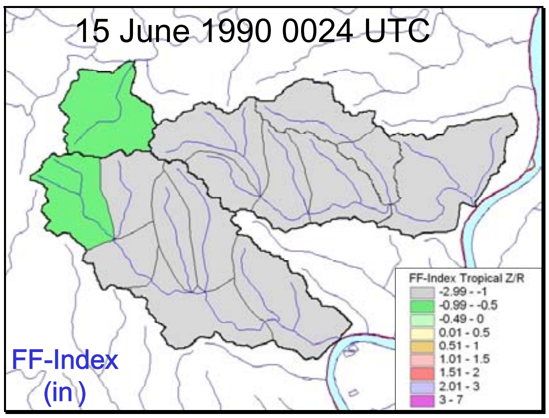

Fig. 18. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0024 UTC using tropical rainfall rates.

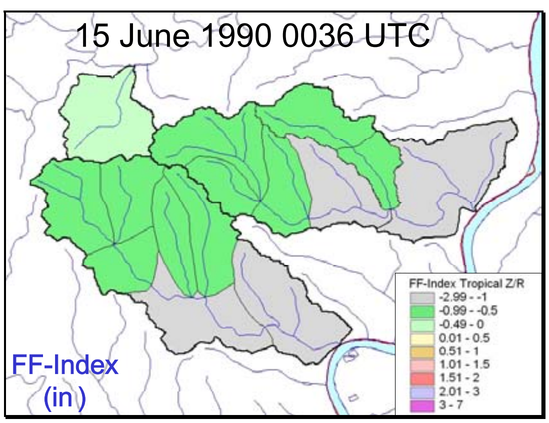

Fig. 19. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0036 UTC using tropical rainfall rates.

A Flash flood warning would likely be issued based on the 0048 UTC ABR (Fig. 19) and the fact that high ABR Rates continue in the headwaters of Wegee and Pipe Creeks.

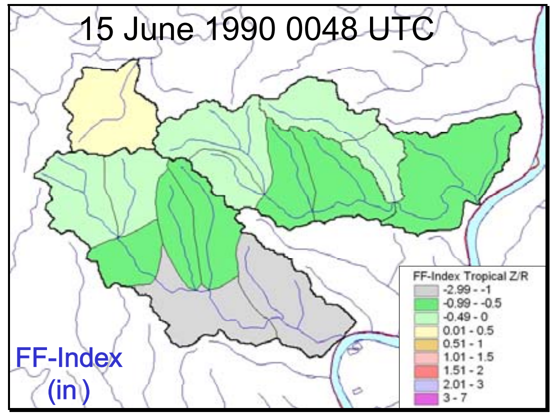

Fig. 20. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0048 UTC using tropical rainfall rates.

By 0900 UTC (Fig. 21) significant flooding problems should be starting to occur. Cumberland Run and two headwaters areas of Wegee Creek are now between a half-inch and one inch of ABR over FFG, and the headwaters area of Pipe Creek has risen over FFG for the first time.

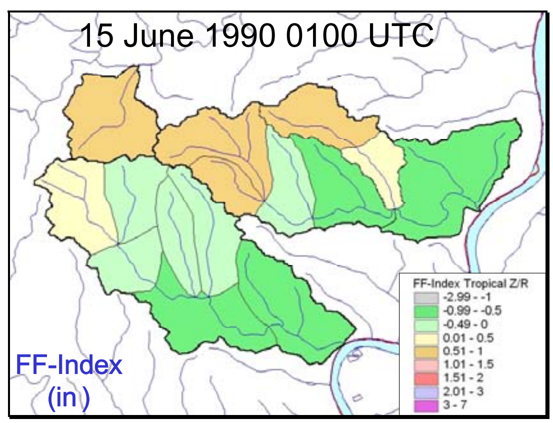

Fig. 21. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0100 UTC using tropical rainfall rates.

By 0112 UTC (Fig. 22) a continuation of high ABR Rates has driven up accumulated ABR in Cumberland Run to almost two inches (red) over FFG and one inch over FFG (pink) in two headwaters areas of Wegee Creek. The headwaters of Pipe

Creek is approaching one inch over FFG. A flash flood statement would be prudent at this point to indicate that severe flash flooding is likely to occur within the next hour.

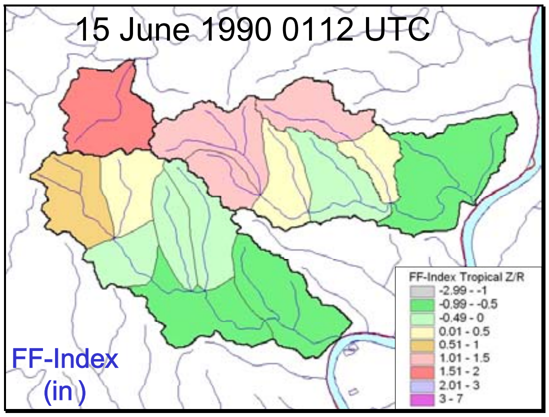

Fig. 22. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0112 UTC using tropical rainfall rates.

By 0124 UTC a serious flash flood event is all but guaranteed in Cumberland Run where ABR is now over two inches above FFG and in Wegee Creek where the headwaters area is now approaching two inches over FFG as well. Pipe Creek is becoming critical as will with ABR over one inch above FFG. Notice that the downstream segments of both Wegee and Pipe Creek (green areas) are well below FFG. Of the 26 fatalities that will occur in the next hour, 24 of the residents live along Pipe

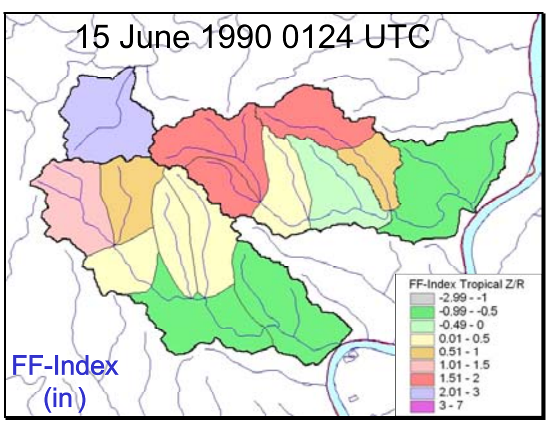

Fig. 23. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0124 UTC using tropical rainfall rates.

and Wegee Creeks in the dark green areas adjacent to the Ohio River. The folks living downstream have not experienced the very heavy rainfall occurring in the headwaters area of Wegee and Pipe Creek upstream of their homes. Describing only the heavy rainfall area in a warning or statement may not be sufficient. The movement of the flood wave downstream into areas where little or no rain has fallen can be especially important and should be included in warnings and statements when applicable.

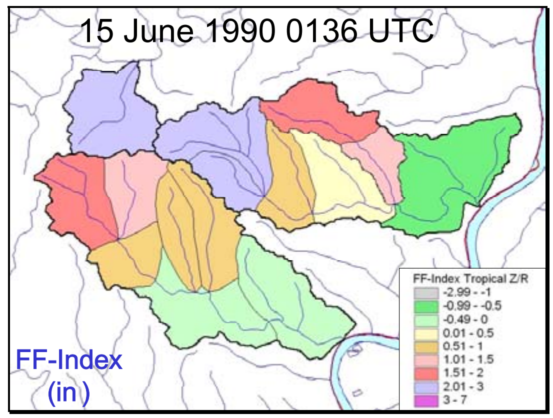

Fig. 24. Shadyside, OH stream basins ABR (in) plot for 15 June 1990 from 0012 to 0136 UTC using tropical rainfall rates.

Recall from Fig. 15 that the standard convective rainfall brought the Cumberland Run and the headwaters of Wegee Creek to only about a half-inch over FFG by 0148 UTC. Figure 17 shows the last plot of FF-Index at the end of the heavy rainfall at 0148 UTC. Use of the standard convective rate may have resulted in a zero lead time warning or statement by 0148 UTC, when the flooding was already well underway. Using the tropical rainfall rate would allow the issuance of a flash flood warning almost one hour earlier at 0048 UTC, greatly increasing the warning lead time.

No rain gage reports were available to verify the occurrence of tropical rainfall rates. Even during the bucket survey no rain gage readings were found in these three watersheds. The only way the forecaster could anticipate the occurrence of the tropical rainfall rates was through the sounding analysis and radar observation of high reflectivity below the zero degree parcel level.

6. USING RAIN GAGES TO VERIFY TROPICAL RAINFALL RATES.

The Johnstown Flood of 20 July 1977 will be presented to demonstrate how rain gages can be used in conjunction with radar rainfall estimates to determine the occurrence of tropical rainfall rates. Digital storm total rainfall data from RADAP will be compared with 24-hour rain gages report.

RADAP was installed at the Pittsburgh, PA NWS office in 1976 and some digital radar rainfall estimates from RADAP were available during the Johnstown event. Saffle and Green (1978) published a paper showing the storm total RADAP rainfall for the Johnstown flood. Two different formats, the Base scan (B-scan) format in a polar two-degree by one nautical mile format with rainfall rounded to the nearest inch, and rectangular grid format of 3 nm by 5 nm (R-grid) which averages the B-scan rainfall into the larger rectangular grid. Fig. 25 shows the B-scan rainfall for the twenty-four hours ending at 1200 UTC on 20 July 1977. A graphic display of the B-scan data was not available to the Pittsburgh NWS office until 1985 (Davis and Rossi 1985). Notice that several 8-inch (200 mm) rainfall maxima (red) occurred in Cambria County. A graphic printout of the R-grid was available to the Pittsburgh NWS office in 1977. The storm total printout of the R-grid data at 1200 UTC on 20 July 1977 shows a maximum of 7 inches of rain in one grid box and 9 grid boxes with 6 inches of storm total rainfall.

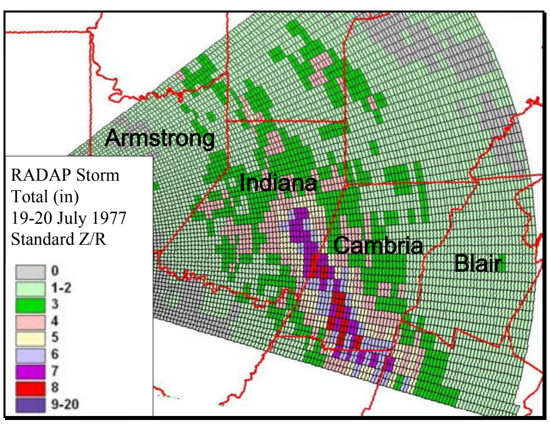

Fig. 25. RADAP B-scan storm total rainfall in inches for 1200 UTC 19 July 1977 to 1200 UTC 20 July 1977 using standard convective rates.

Figure 26 shows a zoomed in view of the rainfall maximum in southern Cambria County The great majority of 78 fatalities occurred in three small watersheds near Johnstown: Laurel Run, Solomon Run, and Clapboard Run. The FFMP watershed boundaries of these three basins are shown as green lines in Figs 26 and 27. The rain gage values plotted in Fig. 26 are from Brau (1978) and are shown in Table 3.

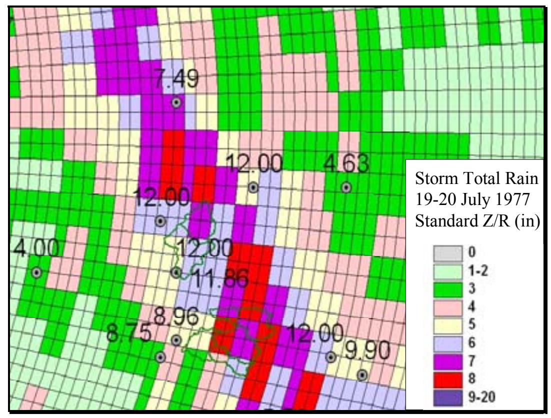

Fig. 26 RADAP B-scan storm total rainfall in inches using standard convective rates for 1200 UTC 19 July 1977 to 1200 UTC 20 July 1977 in Cambria County. Gray circles are rain gage locations rainfall in inches plotted in black. Green boundaries show stream basin boundaries of Laurel Run, Clapboard Run, and Solomon Run.

Table 3. Rain gages in Cambria County of 24-hour storm total ending at 1200 UTC on 20 July 1977 (Brau 1978).

Station Name	Rain (in)	Rain (mm)
Near Laurel Run Dam	12.00	305
Near Cramer	12.00	305
Near Dunlo	12.00	305
Nanty Glo	12.00	305
Laurel Run Dam	11.86	301
Dunlo	9.90	252
Johnstown 2	8.96	228
Johnstown	8.75	222
Strongstown	7.49	190
Ebensburg	4.63	118
Cresson	4.00	102

Notice in Fig. 26 that five different rain gage reports of about 12 inches of rain (305 mm) occur where the RADAP rainfall estimates are light yellow or light blue, 5-6 inches of rain (127-152 mm). The use of tropical rainfall rates instead of standard convective rates typically results in at least a doubling of the radar rainfall estimates. Recall that in the Shadyside, OH event of Section 5, the maximum of 1.88 inches in Wegee Creek became a maximum of 4.05 inches when converted to tropical rates. The ideal way to convert the Johnstown rainfall data to tropical rainfall rates is to compute the data using the raw WSR-57 reflectivity values for each 10 to 12 minute RADAP observation. Since that raw radar data is not readily available, the storm total amounts of rainfall of Fig. 26 will be doubled to estimate tropical rainfall rates. Notice in Table 4 that the convective rates used for RADAP are even less than the standard convective rates used for the WSR-88D. A doubling of the RADAP values will be a conservative estimate of the WSR-88D tropical rainfall rates that produced the Johnstown flood.

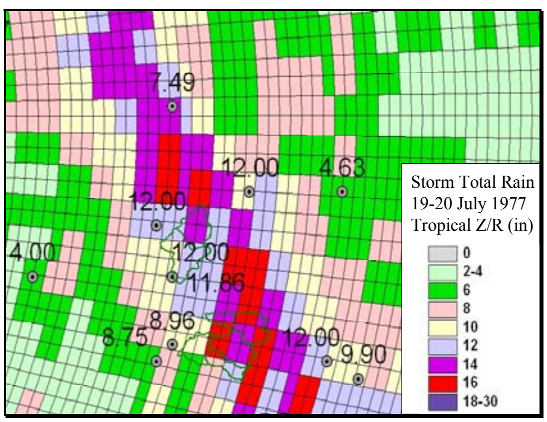

Fig. 27 RADAP B-scan storm total rainfall in inches using standard convective rates for 1200 UTC 19 July 1977 to 1200 UTC 20 July 1977 in Cambria County. Gray circles are rain gage locations rainfall in inches plotted in black. Green boundaries show stream basin boundaries of Laurel Run, Clapboard Run, and Solomon Run.

The Pittsburgh WSR-57 did not show any reflectivity values higher than 48 dBZ through the period of heavy rainfall, another indication that warm rain processes dominated during this event. If the standard convective RADAP rainfall estimates do in fact need to be at least doubled, then the maximum rainfall that fell on Johnstown was at least 16 inches (406 mm). Notice that the largest radar rainfall estimates fell almost equidistant between the rain gage sites.

Table 4. Convective rainfall rates (mm hr^{-1}) used for RADAP and the WSR-88D*.

dBZ	RADAP	Standard*	Tropical*
40	11.5	12.2	21.6
41	13.3	14.4	26.2
42	15.4	17.0	31.8
43	17.8	20.0	38.5
44	20.5	23.6	46.6
45	23.7	27.9	56.5
46	27.3	32.8	68.4
47	31.6	38.7	82.9
48	36.5	45.6	100.4
49	42.1	53.8	121.6
50	48.6	63.4	147.4
51	56.2	74.7	178.5
52	64.8	88.1	216.3
53	74.9	103.8	262.1
54	86.5	122.4	317.5
55	99.9	144.3	384.6

A flash flood warning was issued for Cambria county around 0600 UTC on 20 July 1977 when the RADAP radar estimates reached about 4 inches (100 mm). The 3-hour FFG for Cambria County on 19-20 July 1977 was 3.9 inches. Flash flooding was already underway when the warning was issued. If tropical rainfall rates could have been employed on RADAP, over eight inches (200 mm) of rain would have been indicated by 0600 UTC and upwards of 4 inches (100 MM) of rain would have been indicated as early as 0300 UTC, providing several hours of life saving lead time. The real time use of tropical rainfall rates can be critical to the timely issuance of flash flood warnings.

The best way to verify the occurrence of tropical rainfall rates is to directly compare rain gage measurements with radar rainfall estimates when possible. None of the rain gages in the above analysis were available to the Pittsburgh, PA NWS office in real time. In Section 7 the Homeworth, OH flash flood will be presented as an example of how this real time gage comparison with radar rainfall estimates can greatly aid the in the flash flood warning decision.

7. REAL TIME RAIN GAGE COMPARISONS IN THE WARNING PROCESS

On 27 July 2003 a significant flash flood struck the western half of Columbiana County, OH with the city of Homeworth one of the hardest hit areas. Tropical rainfall rates had been anticipated as a possibility due to the high PW of 5.14 cm (normal July PW 2.60 cm), moist low-level dewpoints, and a Coal depth of 3.5 km. Available rain gages were being monitored in FFMP as the thunderstorm activity began. The airport in Akron-Canton, OH began receiving rain about 2020 UTC on 27 July 2003 and the rainfall continued through 0000 UTC on 28 July 2003. Comparisons of the radar rainfall estimates for the Akron-Canton, OH airport rain gage with the rain gage measurement indicated significant radar underestimation. Table 5 shows the accumulated rainfall for the rain gage at the airport and the radar rainfall estimates from the FFMP program.

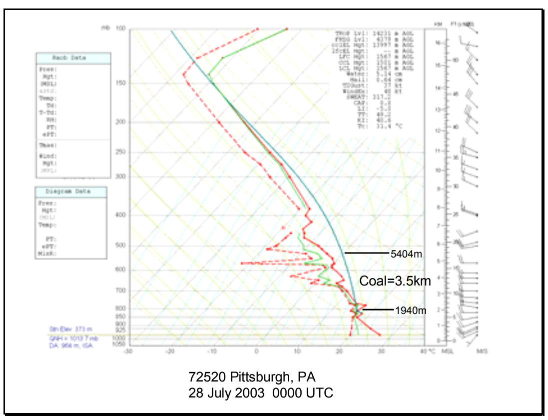

Fig. 28. Sounding analysis for Pittsburgh, PA on 28 July 2003 at 0000 UTC. Coal is the depth of the coalescence layer in km.

The radar underestimation verified that tropical rainfall rates may indeed be occurring and the radar rainfall estimates as indicated by FFMP were doubled to account for the difference. As a result a flash flood warning was issued for Columbiana County before the doubled values of ABR reached the 1-hour FFG value of 36 mm. The three-hour ABR total for the storm based on standard convective rainfall rates is shown in Fig. 29. These totals can be about doubled to estimate the actual rainfall that resulted from the tropical rainfall rates experienced during the flood. A more detailed view of the FFMP stream segments near Homeworth is show in Fig. 30. The city of Homeworth was specifically mentioned in the flash flood warning as the single FFMP basin with the maximum ABR was the

Table 5. Accumulated rainfall (mm) at the Akron Canton, OH airport for 2000 UTC on 27July 2003 to 0000 UTC on 28 July 2003.

Time UTC	Radar Estimate (mm)	Rain Gage (mm)
2000	0	0
2015	0	0
2030	1.3	10.7
2045	4.3	22.9
2100	7.4	24.9
2115	11.6	25.7
2130	20.1	30.2
2145	21.8	38.6
2200	27.4	40.6
2215	33.5	54.9
2230	41.1	70.6
2245	46.7	82.3
2300	49.3	90.2
2315	49.8	91.4
2330	50.0	92.2
2345	51.1	93.5
0000	52.6	95.0

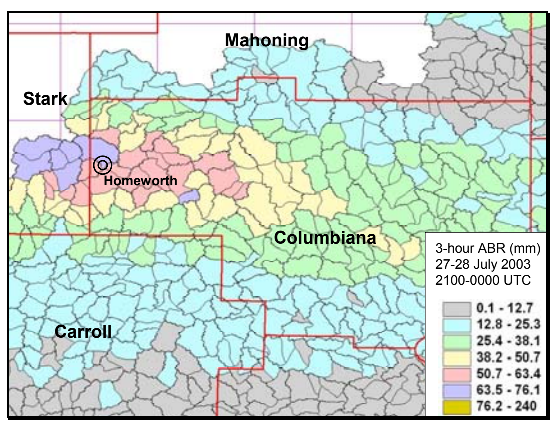

Fig. 29. Three-hour ABR (mm) for Columbiana County, OH from 2100 UTC 27 July 2003 to 0000 UTC 28 July 2003 using standard convective rainfall.

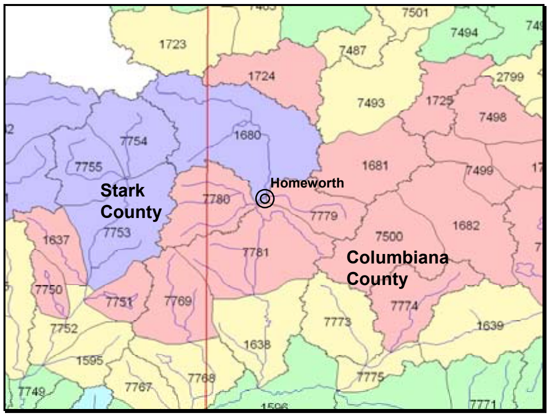

Fig. 30. Three-hour ABR (mm) for Homeworth area of Columbiana County, OH from 2100 UTC 27 July 2003 to 0000 UTC 28 July 2003 using standard convective rainfall. Black numbers are FFMP basin id numbers.

Headwaters of the Middle Branch of Sandy Creek (FFMP ID 1880) that flows directly into the city of Homeworth. About one hour after issuance of the flash flood warning the county Emergency Management Agency (EMA) Office called to report serious flooding in Homeworth, OH. By 0000 UTC the EMA asked that a mention be made in a Flash Flood Statement that travel on all roads in western Columbiana County was discouraged until the flood waters receded. This flash flood warning was successful because of the anticipation of tropical rates.

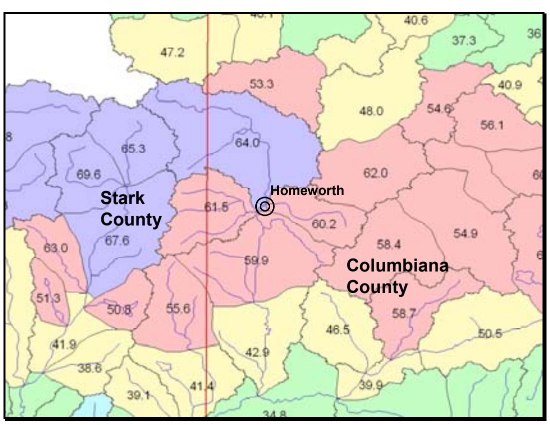

Fig. 31. Three-hour ABR (mm) for Homeworth area of Columbiana County, OH from 2100 UTC 27 July 2003 to 0000 UTC 28 July 2003 using standard convective rainfall. Black numbers are three-hour ABR values in mm.

A warning would not have been issued before the first report of flooding if standard convective rainfall rates had been used.

The Homeworth, OH flash flood is not the only tropical rainfall rate flash flood case that occurred in 2003. A severe flash flood struck the Kansas Turnpike on 31 August 2003 (Table 2) resulting in the death of a mother and four children. Warm rain processes were likely at work in this event as discussed by Kelsch (2004). The details of the Kansas flood will be left to the Kelsch paper, but the sounding for the event (Fig. 31) is included for comparison with the other warm rain events in this paper. Note high PW of 5.19 cm (normal late August PW 2.77 cm) and Coal depth of almost 4 km.

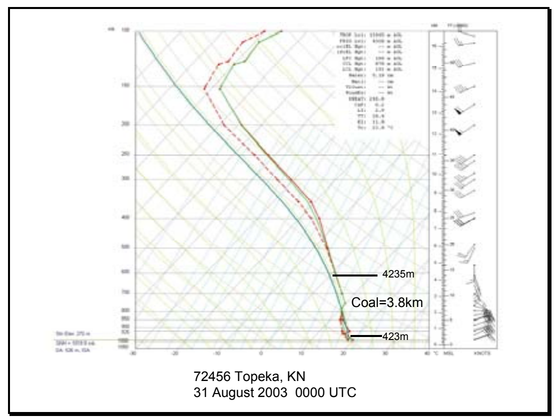

Fig. 31. Sounding analysis for Topeka, KN on 05 October 1998 at 0000 UTC. Coal is the depth of the coalescence layer in km.

8. CONCLUSIONS

Tropical rainfall rates do occur exclusive of tropical storms and the heavy rainfall resulting from these occurrences have resulted in some of the worst flash floods in United States history. The importance of anticipating the occurrence of tropical rainfall rates can not be understated. The use of standard convective rates will result in gross underestimation of the observed rainfall and can result in missed or late flash flood warnings.

The solution is not to use tropical rainfall rates at all times. The occurrence of tropical rainfall rates is a relatively rare event, probably occurring less than one percent of the time exclusive of tropical storms. The best solution would be for FFMP to maintain two parallel databases of rainfall, one with standard convective rainfall rates and a second database of tropical rainfall rates. The forecaster could toggle back and forth between these databases when conditions warrant the possibility of tropical rainfall rates. The WSR-88D can not easily support two separate databases for both tropical and standard convective rates. As the Radar Product Generator (RPG) software is now structured one or the other must be selected for use with the precipitation algorithms. A second option would be to make the change at the RPG level and maintain a database of both tropical and standard convective rainfall on the radar. This would require a multiple suite of rainfall products, one set for tropical rainfall rates and a second set of rainfall products for standard convective rates. These changes would likely be easier and more quickly implemented within FFMP.

The addition of the real-time rain gage comparisons within FFMP in 2003 provides a critical tool for the detection of tropical rainfall rates. The key to the successful application of this tool is the availability of real time rain gage information.

All flash floods are relatively rare events. Flash floods the magnitude of Johnstown, PA and Big Thompson, CO are once in a career warning opportunities. FFMP is structured to catch these major catastrophic events, even in very small watersheds. Only the correct application of the available WSR-88D rainfall information will result in positive results. FFMP is subject to all the limitations of the WSR-88D rainfall estimates, and forecaster application of these strengths and limitations will result in successful flash flood warnings.

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