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HAIL DAMAGE: PHYSICAL METEOROLOGY AND CROP LOSSES

STEVEN ROGERS*
ECOSTAT, Inc.
Post Office Box 237
Highland City, Florida 33846

Abstract. **Hail damage is a rare and potentially devastating category of environmental plant injury in Florida. A severe hailstorm swept through Central Florida on the afternoon of Saturday, March 30, 1996, causing total damages approaching $25 million. Hailstones with diameters exceeding 4.5 in were reported by some storm observers. Nearly all hailstones observed were roughly spherical in shape. Shifted gamma distribution analysis confirmed that hailstones of this size were reasonable given the observed hail size distribution. Calculations of ice density, air density, drag coefficients, gravitational acceleration and the energy required to lacerate citrus rinds in the observed "inverted-V" pattern indicated that the terminal velocity of many hailstones at impact exceeded 100 mph. Many individual fruits were ripped completely in half by the hailstone shock, while leaves and branches were extensively tattered and torn from the trees. Some growers had signed crop sales contracts just prior to March 29, 1996, with harvests scheduled for the beginning of April, 1996. Unfortunately, damage to fruits from this hailstorm rendered these crops unharvestable. Estimated economic crop damages in some grapefruit and orange groves were 100% (approximately 700 boxes per acre). An estimated spot value of $3.00 to $3.50 per grapefruit box thus resulted in some insurance-adjusted crop losses approaching $1500 per acre. This paper presents a review of hailstorm meteorology and photodocumented evidence of one of the worst hailstorms damaging citrus in recent Florida history.**

Introduction

Hail damage is a rare and potentially devastating form of citrus crop injury in Florida. Specific incidents of hail damaging Florida citrus have been poorly documented since growers are usually unprepared to acquire and interpret scientific information regarding the amount and type of hail that damages their crops. Interestingly, crop damages caused by hailstones in the United States have historically been enormous, amounting to about 8% of all crops in some years. Prior to about 1960, crop damages comprised about three-quarters of total U.S. hail losses overall (Flora, 1956; Malone, 1951). As American society has evolved from agrarian to urban, greater hail losses today occur to metropolitan structures such as houses and automobiles. For example, a 1992 hail storm in Orlando, Florida caused $60 million in damages and was ranked as that city's worst natural disaster (Hughes and Wood, 1993), exceeding even the damage caused by Hurricane Donna in 1960 (Henry et al. 1994). Hurricanes, tornadoes and lightning command more dramatic attention, but worldwide, hail ranks as one of the most dangerous and destructive of all severe weather phenomena.

Currently, no economic loss figures exist for hail damage to citrus. References to hail in the citrus literature are usually limited to a notable damage photograph and a short descriptive paragraph about the uniqueness of the climatology (Browning et al. 1995; Futch and Jackson, 1995; Klotz and Fawcett, 1973; Knorr, 1973; Tucker et al. 1983). Hail damage is not even indexed in any edition of Citrus Growing in Florida (Jackson, 1991; Ziegler and Wolfe, 1975). Prior to this article, the most extensive discussion on hail injury in citrus was by Turrell (1973), but it provides little meteorological insight into the giant hail formation processes resulting in near total crop losses. On many crops (including citrus (Witz, 1982)), considerable effort has been expended into hail suppression research particularly in the former Soviet Union (Burtsev, 1980a; Busch, 1974; Mesinger and Mesinger, 1992). However, all citrus references implicitly agree that little that can be done to prevent hail damage due to the cost of management and the constantly changing conditions present in hailstorms that preclude forecasters from issuing sufficiently advanced warnings.

On March 30, 1996, at approximately 2:30 p.m., a severe hailstorm occurred in Polk County that resulted in substantial crop losses to citrus. Total urban and agricultural losses associated with the storm approached $25 million. The storm migrated eastward through Polk County from eastern Hillsborough County and traveled through parts of Lakeland, Highland City, Bartow and Lake Wales. Tornadoes and hailstones exceeding the size of softballs were reported in this storm. Unfortunately, the small temporal and spatial windows of severe convective storms that produce giant hail (i.e., hail greater than about 2 to 3 in (7 cm) in diameter) preclude their being thoroughly examined through the conventional meteorological observation system (Aydin et al. 1995; Barber and Mahrt, 1981; Schmid et al. 1992). However, numerous studies of hail storm physics from other global geographies discuss events in which smaller-sized hail occurred. This paper pieces some of these studies together in a speculative way with our observed data inferring conditions leading to development of the giant hail storm that occurred on March 30, 1996. A review of the physical meteorology and photodocumented evidence of one of the worst hailstorms damaging citrus in recent Florida history is presented.

Materials and Methods

Synoptic Features of the Storm

This strong thunderstorm composed of a tall cumulonimbus cloud with a strong central updraft and vortex met the defined requirements of a supercell. A supercell is thought to be a storm system propagating in a manner that allows it to maintain vigorous circulation that may last for several hours (Miller et al. 1988). Radar reflectivities obtained by the National Weather Service (NWS) in Ruskin, Florida, exceeded 70 dBZ, indicative of very large precipitation particles. (Hail intensity is described in terms of radar reflectivity and dBZ represents the unit of measurement.) Warnings were issued by the NWS as hail was first reported at about 1:40 p.m. near the eastern border of Hillsborough County. Giant hail subsequently precipitated over a large area of Polk County as the storm traveled eastward through Polk County through North Lakeland, Highland City, Bartow and Lake Wales (Fig. 1). Thunder, lightning and tornadoes accompanied the hail storm, and Federal Aviation Administration air traffic controllers reported that the sky turned as "black as ink" immediately prior to some of the hail events (Table 1). Ground temperatures in the county during the storm were approximately 80° F, while temperatures near 50,000 feet approached -100° F. Updraft windspeeds were estimated at over 100 mph from radiosonic data using the Sharp Skew T/ Hodograph program (Hart and Korotky, 1991). Physical weather data correlating crop damages with the geographical distribution of the storm were obtained from the National Weather Service in Ruskin.

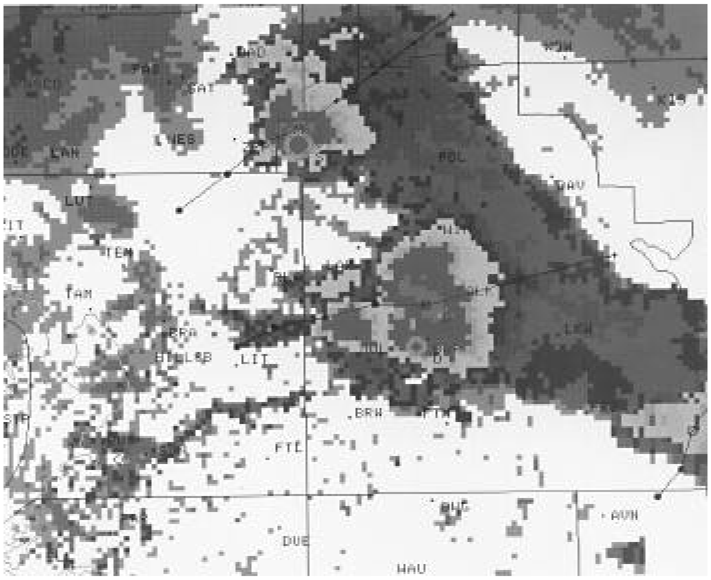

Figure 1. National Weather Service radar map showing reflectivities observed during the March 30, 1996 hail storm that occurred in Polk County, Florida (NWS, 1996). The boundaries of Hillsborough and Polk Counties may be seen on the left and the right of the photograph, respectively. The larger the reflectivity values, the larger are the precipitation particles. Reflectivities greater than about 60 dBZ are indicative of hail. The light color in the center of the map between Lakeland and Bartow (also marked by the O) represents a reflectivity of about 65 dBZ. This is the area in which the damaged citrus groves were located. The horizontal line across the center of the storm represents the calculated storm trajectory

Hailstone Samples

It is very rare to observe large hailstones in Central Florida, so many people at the urban/agricultural interface ran outside when they heard the hail hitting their houses, automobiles and yards. These people collected the unique hailstones and stored them in their freezers. Storm watchers reported their observations to the National Weather Service (Table 1). In response to requests for these hail stones, several people offered their hail for this study. Actual hail samples were obtained from a representative geographical area of approximately 1 square mile, but reported observations were obtained from an approximately 15 mile-wide "belt" across Central Polk County from the western to the eastern border. Over the next week, the hail stones were measured, grouped and photographed. Hailstones were cut with a thin-blade hacksaw and the internal structures of the hailstones were photographed and examined macro- and microscopically under both overhead and transmitted light.

Crop Damages

Crop damages were surveyed during the storm, immediately following the storm, at weekly intervals after the storm for approximately 8 weeks, then again in October, 1996. Leaves, branches and fruits with representative injuries were selected, macro- and microscopically examined and characteristic indicators of damage and disease were photographed.

Data Analysis

Quantitative data were analyzed with Statview 4.5 (Abacus Concepts, Berkeley, CA) and Microsoft Excel (Microsoft Corp., Seattle, WA). Differential equations were studied and plotted using the MathCad analysis engine (MathSoft, Inc., Cambridge, MA). Graphs were plotted in DeltaGraph Pro 3.0 (DeltaPoint, Monterey, CA) under a Macintosh System 7.5 processing platform. All physical calculations were performed using standard scientific and metric units and transformed into English units using accepted conversion procedures (Serway and Faughn, 1989).

Results and Discussion

Hail in Florida

Florida may have more thunderstorms than any other state in the U.S. and the atmospheric conditions inside these storms often favor hail formation. Hail of any size is not nearly as common in Florida as in other states (Chen and Gerber, 1990; Miller, 1981). Since most hail storms in Florida occur in the spring (54%) and summer (35%) between 1 and 2 p.m., the rarity of hail in the state is due to a thick layer of warm air at the earth's surface that tends to melt much of the hail before it hits the ground (Henry et al. 1994). Nearly all sections of Florida, including Key West, have experienced hail. However, cities in the panhandle average only about one hail day per year, while other areas of the state can expect hail only about once every three years (Henry et al. 1994). An informal survey of growers and weather observers suggested that a giant hail event at a given location in Florida occurs only once or twice every 100 years.

Hail precipitation generally occurs as lumps of ice greater than about 0.2 in (0.5 cm) in diameter (Mather, 1974). It is formed when small embryonic ice pellets less than about 0.05 in (1 mm) in diameter ("graupel") nucleate and remain airborne for a sufficient time in thunderstorms. In these circumstances, in which supercooled water (i.e., liquid water below 0° C) is present in adequate atmospheric concentration (Anthes et al. 1975). The ice particles continue to increase in size as they circulate around turbulent vertical and horizontal storm drafts. Eventually, the mass of the hailstones exceeds that which can be supported by the air currents, so they fall to the ground. Hailstones are usually spherical, but can also be ellipsoidal, oblate, conical or iciclelobed in shape (Takahashi, 1987). They range in diameter from about 0.2 in (0.5 cm) to over 5.5 in (13.97 cm), but hailstones much larger than about 5 in (12.7 cm) are often attributed to the aggregate freezing of several smaller particles, especially if they deviate from the common spherical form (Hughes and Wood, 1993). Extremely turbulent conditions (described below) are required to create giant hail exceeding the size of baseballs. Equatorial cross-section slices of hailstones often reveal concentric, up to 25 clear or cloudy layers (Hughes and Wood, 1993). Like tree rings, "hail rings" can provide information about the physical and environmental conditions under which the hail was formed.

Storm Features that Favor Large Hailstone Formation

The constantly changing conditions present in hailstorms defy thorough analysis and understanding of the processes involved, and there are few, if any, scientific investigations of stormsthat produce hail in Florida. However, a analysis of a number of hail studies unveiled features of thunderstorms that favor formation of large hailstones. Very strong drafts of horizontal, vertical and downward air are common (Miller et al. 1988; Musil et al. 1991). Generally, updrafts appear to be more numerous and more intense than downdraft regions. Forexample giant hailproducing storms were found to exhibit greater horizontal extents and higher speeds than storms producing smallersized hail (Musil et al. 1991). The drafts also appear somewhat more turbulent in large hailproducing storms.

Table 1. Chronological compilation of some storm data and unusual weather phenomena reported during the March 30, 1996 giant hail storm (NWS, 1996).

Location	Time	Estimated $ Damages	Storm Notes
Hillsborough County	1:55 PM	$75,000	1.75 in
Riverview	Sporatic golfball-sized hail caused paint damage to a few vehicles and damaged the roofs of a few homes and businesses in Riverview near U.S. Highway 301.		
Hillsborough County	2:00 PM	200,000	1.75
Valrico	Golfball-sized hail caused paint damage to several vehicles and damaged the roofs of many homes and businesses in Valrico along State Highway 60.		
Polk County	2:40 PM	20,000	1.75
Lakeland	Thunderstorm winds caused minor damage to the roofs of several homes in Medulla along State Road 37.		
Pasco County	2:45 PM	—	1.75
Zephyrhills	Penny-sized hail reported at the Zephyrhills Municipal Airport.		
Polk County	2:45 PM	250,000	2.75
Mulberry	Baseball hail damage to hundreds of vehicles and several homes in Mulberry. Windows shattered. Hail drifted up to eight inches deep in a few locations.		
Polk County	2:50 PM	1,500,000	1.75
Lakeland	Golfball-sized hail produced widespread paint and glass damage to numerous vehicles in and around Lakeland. Many homes also received minor to moderate roof damage from the large hail. Hail accumulated to a depth of up to eight inches in several low lying areas of shopping centers, roadways and fields in and around Lakeland. Numerous reports that golfball-sized hail stripped the leaves and small branches off trees and plants, mainly over southern portions of Lakeland between State Road 37 and U.S. Highway 98.		
Polk County	3:15 PM	300,000	Wind
Bartow	An 86 mph wind gust was reported by FAA Tower personnel. The tower suffered window and roof damage. Airport tower personnel reported the sky turned black as ink just prior to the onset of the damaging wind. One parked aircraft incurred minor structural damage when it was pushed by thunderstorm winds into the wall of a hanger. Thunderstorm winds overturned and demolished five mobile homes on wheels at the Homes of Merit mobile home plant located at the Bartow Airport. Three additional mobile homes at the plant incurred minor structural damage. The roofs and doors of two businesses at the airport were also severely damaged by downburst winds.		
Polk County	3:35 PM	—	Tornado
Lakeland	A short-lived tornado touched down sporadically in a rural area of northern Polk County near the intersection of U.S. 98 and Rock Ridge Road.		
Polk County	4:00 PM	24,000,000	4.55
Lake Wales	Hail, most the size of baseballs and a few the size of softballs severely damaged the roofs and knocked out windows in nearly 600 homes in Lake Wales. The local fire station reported hail covered the ground nearly six inches deep during the peak of the hailstorm which lasted 15 minutes. Most of the damage was on the north side of homes and buildings. Estimated damage to homes and businesses was nearly $15 million. Hail severely damaged the surfaces and knocked out the windshields of up to 3000 vehicles in the Lake Wales area. Hail damage to vehicles was estimated at nearly $9 million. Several trees were stripped of leaves and small branches by mostly baseball-sized hail in the Lake Wales area.		

Updrafts must be sufficiently strong that large hail particles can remain aloft for an extended period of time (sometimes approaching 15 minutes) and simultaneously encounter an adequate concentration of supercooled liquid water that can readily accrete to the growing ice particle (Malone, 1951). There appears to be a positive correlation between the size of hailstones and horizontal extent of the updrafts (Nelson, 1983), the speed and temperature of the updraft (Dennis and Musil, 1973), and the temperature differentials between the clouds and the ambient air (Turrell, 1973). The width of the updrafts may exceed nearly 2 miles (3 km), while the downdraft size is likely to be somewhat smaller in width (Musil et al. 1991). Upper limits for updraft widths can approach 10 miles (15 km) when downdraft widths occur near 5 miles (8 km), so it appears as if updraft extent can be nearly 2 times greater than downdraft width in giant hail storms. There also appears to be a positive relationship between the strength of the updraft and the observed hailstone size (Musil et al. 1991). (This relation is expected since larger storms are generally more turbulent and tend to exhibit stronger upward vertical motions.)

In a storm that produced up to 2 in (5 cm) hailstones, Musil et al. (1991) found that vertical wind velocities in the drafts ranged from about -45 mph (-20 m sec^{-1}) to almost 120 mph (53 m sec^{-1}), with weighted mean vertical speeds of about 15 mph (7 m sec^{-1}) and 12 mph (5.5 m sec^{-1}) for updrafts and downdrafts, respectively. It was noted that the updraft region was stronger than the downdraft region. Hail was found in storm sectors of moderate updraft, but some parts of the storm were also noted to be hail-free. Consistent with previous studies, larger hailstones were observed in storms with stronger updrafts, demonstrating that strong updrafts (Musil et al. 1991) as well as broad regions of at least moderate updraft strength (Nelson, 1983) permit more time for the development of larger hail.

Growth of Large Hailstones

Research from other storm systems indicated that some of the largest hailstones developed in a mesocyclone near the circulation center of the storm (Miller et al. 1988). (The middle-level mesocyclone is closely related to tornadogenesis (Lemon and Doswell III, 1979).) As implied in the above discussion, there appear to be at least two variables required for development of large hailstones in such mesocyclones: 1) a very high-speed updraft, and 2) sufficient residence time of the growing hailstone in the updraft (Miller et al. 1988). (Residence time depends upon the type of horizontal path that an accreting ice particle follows.) Thus, hailstones ranging in diameter from about 3 to 4 in (8 to 10 cm) were generated from tightly spiraling trajectories that remained close to the storm's primary circulation center (Miller et al. 1988). Giant hail could be produced from less than 0.25 in (0.64 cm) frozen drops nucleated near the circulation center. The updraft vertical profile required a speed approaching or exceeding 100 mph to sustain the growth of giant hail.

Equatorial cross sections of the spherical hail obtained from the March 30, 1996 storm revealed a clearly defined pattern of concentric, circular rings. Translucent nucleation embryos were evident in the centers of the hail. The translucent embryos suggested that large frozen droplets may have served as growth substrates for many hail stones in this storm. From the translucent centers, ice rings extended more or less symmetrically outward to a radial distance of approximately 1.25 in (3 cm). It was difficult to determine the original ice embryo size by visual appearance only; however, the symmetric growth pattern suggested that the initial droplet size was comparatively large. The outwardly layered concentric rings were alternately clear and opaque in appearance, suggesting that the hail underwent a wet-dry growth cycle. Alternatively, the clear appearance may be due to the accretion of large frozen drops, while the opaque appearance may be due to the accretion of much smaller cloud droplets. As in Miller et al. (1988), no claim is made that the nucleation and growth procedure described above necessarily accounts for all the hail produced in the storm.

Maximum Likely Hailstone Size

Several statistical approaches have been described for estimating the maximum hailstone size to impact an area, including hailpad observations and exponential distribution analysis. However, research has shown that maximum hailstone sizes, or the upper truncation point for the size distribution, cannot reliably be established from hailpad observations. This is due to the frequent observation that the largest hailstone to strike a hailpad is often smaller than the largest hailstone observed in the immediate vicinity (Bardslay, 1990; Smith and Waldvogel, 1989). Hailstone size distributions also may deviate substantially from the exponential distribution, invalidating size estimates if departures from the exponential form result from wind sorting, melting of smaller stones, insufficient sampling durations or sampling location effects (Wong et al. 1988).

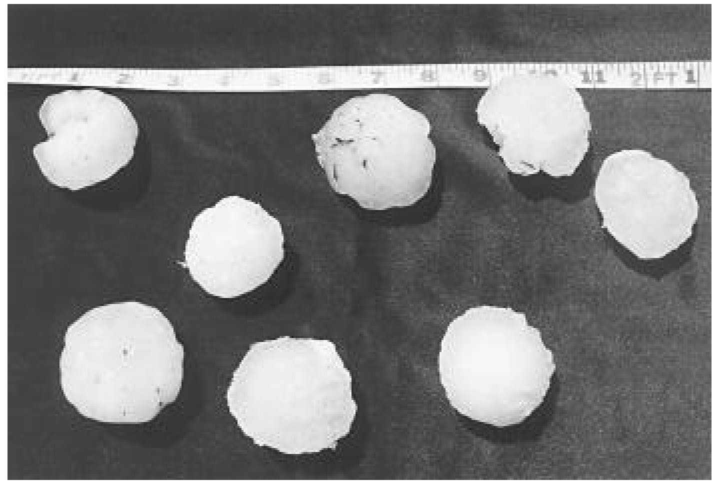

Figure 2. Visual representation of the size distribution of hail that occurred in the citrus groves affected by the March 30, 1996, storm. Although hail sizes ranged in size from less than 0.5 in (1 cm) to greater than 4.5 in (11.4 cm), many observed hail particles were in the 2.0 to 3.0 in (5 to 7.5 cm) size range. The hail shown in this figure appears somewhat smaller due to the melting that occurred in the field before collection and sublimation that occurred in the freezer during storage.

While the exponential approach for maximum hailstone size determination is acceptable for many applications, a shifted gamma size distribution (Evans et al. 1993):

$$N(D)dD = \frac{N^*}{\Gamma(\alpha)b^{\alpha}} D^{\alpha-1} \exp(-D/b)dD$$

where $N(D)dD$ = the particle number per unit volume; D Š 0; $a > 0$; $b > 0$, and;

$$\Gamma(a) = \int_0^{\infty} t^{\alpha-1} exp(-t)dt$$

often provides a better fit to observed data than the exponential distribution (Wong et al. 1988), especially if factors influencing the deviation of data from the ideal exponential curve occur. N^*, the particle concentration parameter, is estimated from the sample after estimates of the shape parameter, a, and b, the scale parameter, have been obtained. Since the exponential form falls as a special case of the gamma distribution, the shifted gamma distribution was preferred for our analysis due to its ability to characterize size distribution shape.

For any statistical determination of the maximum hail size to impact an area, two core assumptions must be met: 1) the sampling area supplied with hailstones must be generated from the same hailstone size distribution as the total site under consideration, and; 2) the hailstone impact points must be randomly distributed throughout the sampling area. For our analysis, α was set at the median value, 2.0, N^* was approximated by $n,$ the total number of stones and β was defined as $D'/2$, where D' was the mean of D (Wong et al. 1988). Given these assumptions and the possible inaccuracies due to our limited sample area and duration, gamma distribution analysis of the sampled hailstone data suggested that the majority of hailstones falling in the March 30, 1996 storm data observation sites were in the range of about 2.0 to 3.0 inches in diameter. This calculation was fairly consistent with field observations (Fig. 2). The 4.5 in (11.43 cm) maximum hailstone size reported to occur (Table 1) was determined to fall within the reasonable boundaries of this size distribution.

Crop Damages

A March, 1990 hailstorm producing quarter-sized hail ruined half of a 2000 acre potato planting in the northern section of the Florida peninsula (Henry et al. 1994). Otherwise, crop damages associated with hail in Florida are poorly documented. In fact, the NWS did not have any official estimates of crop damages associated with the March 30, 1996 hail storm in Polk County (Table 1). However, several unharvested citrus groves were in the path of the storm and included red grapefruit and orange varieties targeted for fresh markets. The hail storm caused biological losses of approximately 90% with the trees exhibiting extensive leaf loss and 30 to 50% of the crop knocked off the trees. Leaves were extremely tattered and both leaves and small branches were ripped to the ground. Some fruits on the ground appeared with undamaged rinds, so strong winds may also have contributed to the crop losses. Bark lesions such as those depicted in Knorr (1973) and described in Tucker et al. (1984) were extensive.

Some recently set fruits that were to mature the following season were damaged or dislodged, so the storm affected the following season's crop and tree health. Of those fruits that remained on the trees, many showed hail lesions that completely severed up to half of the fruit (Fig. 4). On fruits struck to the ground, some were found with approximately 1 in (2.5 cm) hail imbedded in the rind or lodged inside the fruit itself (Fig. 5), indicative of a high energy of impact (Miller, 1981). Interestingly, lesions often occurred in an "inverted-V" shear (Figs. 4 and 5). Although rotated for better viewing, the inverted-V pattern is also evident in the hail damage depicted in Knorr (1973). Apparently, hail initially impacted the upper half of exposed fruits. The energy propelled the hail into the fruit, shearing the rind open as it continued to travel on into the flesh, resulting in the inverted-V laceration. In oranges, if the hail impacted the fruit at a trajectory directed toward the central axis, then it sometimes became imbedded in the fruit. However, if the impact trajectory was directed off-center, the velocity of the hail more likely propelled it on past the fruit, severing that sector of the fruit into which it came into passing contact (Fig. 4). Due perhaps to their thicker rinds, grapefruits were more likely to contain imbedded hail, regardless of the impact trajectory of the hail. In almost all instances, the hail lacerations on oranges were more traumatic than on grapefruits subjected to equivalent hail shock.

Site investigations several weeks following the hailstorm confirmed as expected that the damages worsened over time. In addition to oleocellosis resulting from punctured oil gland injuries (such as those described in Knorr (1973) and Turrell (1973)), cumulative fruit droppage increased over time as ethylene-activated abscission cell layers continued to dislodge the injured fruits (Beyer, Jr. et al. 1984). Further, fruit flies, other insects associated with fruit decay and secondarily pathogenic fungi symptomatically identified as *Phytophthora citrophthora*, *Penicillium* spp. and *Endomyces geotrichum* Butler & Petersen, invaded the remaining injured fruit tissues, resulting in injuries and infections sufficient to drop fruit which were not dislodged by the physical impact of the hailstones themselves. Similar infections developed on ostensibly undamaged fruits on the ground, rendering crop salvage operations impractical. It was also increasingly evident that flowering and fruit set were decreased by the hail as the total crop set appeared lower in the hail-affected trees than in comparable trees not exposed to the giant hail.

Seven months after the storm, many of the new season's fruits manifested injuries that developed from the hail impact occurring the previous spring. These were fruits that had recently set prior to the spring storm, but were not dislodged by the impacting hail. These fruit could escape the initial dislodging due to their small size and comparatively elastic rind, which enabled them to be knocked to the side as the hail came into contact with them. The injuries appearing on these fruits later in the year consisted primarily of "pockmark" lacerations of the rind, similar to those described in Browning (1995), Klotz (1973) and Pratt (1958). Parasitic microarthropod populations (e.g., *Phyllocoptruta oleivora* Ash.) and greasy spot disease (*Mycosphearella citri* Whiteside) did not appear dramatically different on the hail affected fruits and leaves—at least at the 3 to 6 ft (1 to 2 m) height at which most fruits were sampled. Wood rots (Browning et al. 1995) were found to occur on some of the hail damaged branches, especially those in which the terminal points were

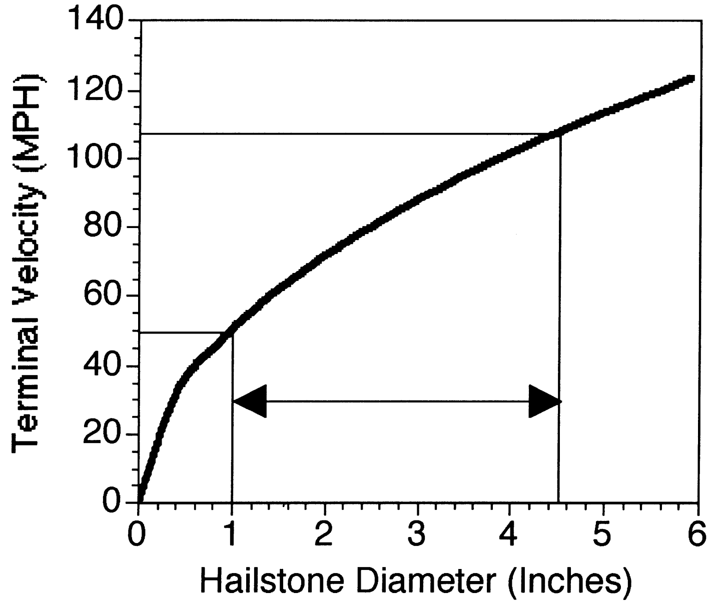

Figure 3. Terminal velocity of hail as a function of increasing diameter. The velocity of hail to occur in the storm was calculated to range from about 50 mph (22.4 m sec^{-1}) to nearly 110 mph (49.2 m sec^{-1}). The area delineated between the vertical lines and the double arrow represents the range of velocities of many hailstones.

Figure 4. Catastrophic injuries occurring to fruits in the spring hail storm. Halves of many fruits were severed. Nearly 50% of the fruit was dislodged from the trees and leaves and small branches were extensively tattered and torn. Note the "inverted-V" pattern of injury.

Figure 5. Hail impacted inside a grapefruit. A blunt object, such as a spherical hail particle, must have a very large velocity to impact the thick grapefruit rind and become lodged in such a fashion. Note the "inverted-V" pattern of injury.

severed or killed. However, most sub-terminal branch lesions were found to be healing over and the leaves and fruits on these branches appeared relatively healthy, although maturing somewhat earlier than usual. Many tattered and torn leaves did not exfoliate, but were found still to be attached to the trees in the fall, enabling them to continue sourcing photosynthates to the maturing crop.

Crop and economic losses from the hail storm extended into the following season. Dead wood was more prevalent in the hail-affected groves than in groves that escaped the storm, especially in the tops of the canopies most exposed to the direct impact of the incoming hail. In fact, these canopy tops appeared with a preponderance of dead branches, thinned and somewhat "ragged". As a result, the incidence and severity of melanose lesions (*Diaporthe citri* Wolf) appeared somewhat greater in the hail-affected trees, despite the application of an additional 77% cupric hydroxide spray (50% metallic cupric ion) to manage the epidemic. This damage profile suggested that severely hail damaged trees may benefit from a follow-up hedging/topping/cleaning program to help reduce the inoculum potential of melanose disease in subsequent seasons. Standard quality tests indicated that fruits on trees and branches stressed by the hail matured slightly earlier than fruit on trees and branches not subject to the physical hail stress, rendering first market, high value crop harvest operations slightly more difficult to coordinate.

Economic Losses and Insurance Recovery

Some growers signed contracts for the sale of their crops just prior to March 29, 1996, with harvests scheduled for the beginning of April 1996. Unfortunately, damage to fruits from this hailstorm rendered some of these crops unharvestable. During the weeks preceding the storm, crop volume was up, supply was extended and demand in the North American market was sluggish (Carter, 1996; Griffin and Burns, 1996). Thus, contracted spot prices for fresh red grapefruit crops (sizing mostly 40 to 48) hovered around $3.00 to $3.50 per field box. Estimated crop damages in some grapefruit and orange groves ranged from 60% to 100% (approximately 420 to 700 boxes per acre). Gross economic losses in some grapefruit groves thus approached $2500 per acre. Unfortunately, despite the numerous criteria that must be met, citrus catastrophic crop insurance programs did not compensate the growers for 100% of their sustained losses (United States Department of Agriculture/Consolidated Farm Service Agency, 1995). During the 1995-96 crop year for example, insurance costs were $50 per variety (not including the time and expense required to survey the crops and submit the applications), but the grower absorbed the first 10% of the economic losses as well as that portion of the value for which the crop was not insured. Once all factors had been calculated, the growers affected by this hail storm were compensated an average of about one-third to one-half of their total crop losses, resulting in insurance-adjusted crop loss recoveries of about $1000 per acre. Unfortunately, insurance loss estimates did not take into account damages and losses occurring to the following season's crop. Therefore, total economic losses were probably underestimated by the percentage of the next season's crop dropped, diseased or not set as a result of the previous season's hail.

Interestingly, almost 10% of the fruits in these groves escaped damage or excision due to the hail. Unfortunately, crop prices at the time were so low that any partial effort to salvage the crop would not have generated sufficient returns to compensate the growers for harvesting their crops. However, had insurance not been obtained for these crops, the economic losses could have been even greater (Burtsev, 1980b).

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