3.3

THE FREQUENCY OF LARGE HAIL OVER THE CONTIGUOUS UNITED STATES

Joseph T. Schaefer*, Jason J. Levit, Steven J. Weiss and Daniel W. McCarthy
NOAA/NWS/NCEP/Storm Prediction Center, Norman, Oklahoma

1. INTRODUCTION

One of Stan Changnon's abiding interests is the frequency and pattern of large hail occurrence. Stan started publishing papers in AMS journals on the occurrence of large hail in 1966. After that initial effort, Stan has published 27 papers in AMS journals alone. When other journals, such as those of the AGU, Conference Preprints, and Technical Reports are added, Stan has an amazing record of doing productive research about a single phenomenon.

The 1966 paper (Changnon, 1966) was "Note on Recording Hail Incidences." In it, Stan showed how weighing-bucket rain gauges with their evaporation funnels removed could be used to record hail occurrence. Since that initial paper, Changnon has devoted considerable effort to finding segregate data sources for hail observations. A summary discussion of techniques he developed to use insurance loss data to infer hail characteristics appears in Changnon (1999).

The Storm Prediction Center (SPC) has taken a more traditional approach to exploring the pattern and frequency of large hail. The SPC maintains a database of reported severe thunderstorm events over the contiguous United States (Schaefer and Edwards, 1999). Information on "severe hail," i.e., hail of 190 mm (¾ inch) diameter or greater, is available back through 1955.

Since 1972, there has been a concerted effort to maintain agreement between the SPC data and the entries in the NCDC publication *Storm Data*. Prior to that, data were obtained from real time reports collected by the U.S. Air Force. It should be noted that the wind and hail data for the transition year, 1972, are incomplete.

Each hail record contains the time, latitude, longitude, diameter, county, and the number of fatalities and injuries caused by each event. For storms that occurred before 1996, the property damage is simply listed as a logarithmic category that ranges from "0" (< $50) to "9" (> $500,000,000). From 1996 on, property damage estimates are given in millions of dollars.

Hail reports typically come from specific observers, so no information on the path and extent of the hail swath is available. As an arbitrary artifice to quantify the data, hail reports within any given county are required to be separated by at least 16 km or 15 minutes (Grenier and Holmstead, 1986).

2. HAIL REPORT COLLECTION PROCESS

Hail size is usually reported to the NWS as a comparison to the size of a common object. NWS instructions give a typical size for several of these items (NWS, 2003). Table 1 is constructed from the information in the instructions.

The table also contains the footnote:

> *For many years, dime-size hail was the coin type associated with 0.75-inch diameter hailstones. However, the diameter of a dime is 11/16 inch, slightly smaller than a penny, which is 12/16 inch (0.75 inch).*

This note indicates that for several years "dime size" hail was erroneously considered as the smallest severe hail size. Because of this historical confusion, dime and penny size reports are grouped together in this discussion.

Table 1: NWS Hail Conversion Chart

Penny	0.75 inch
Nickel/Mothball	0.88 inch
Quarter	1.00 (15/16) inch
Half Dollar	1.25 inch
Walnut/Ping Pong Ball	1.50 inch
Golf Ball	1.75 inch
Hen Egg	2.00 inch
Tennis Ball	2.50 inch
Baseball	2.75 inch
Tea Cup	3.00 inch
Grapefruit	4.00 inch
Softball	5.40 inch

Thus, although hail size appears to be a continuous variable, it is in fact quantized. This is clearly depicted in the historical distribution of reported hail sizes (Fig. 1). Ten sizes account for 152,046 of the 154,702

Corresponding author address: Joseph T. Schaefer, NOAA, NWS Storm Prediction Center, 1313 Halley Circle, Norman, OK 73069-8493; e-mail: joseph.schaefer@noaa.gov.

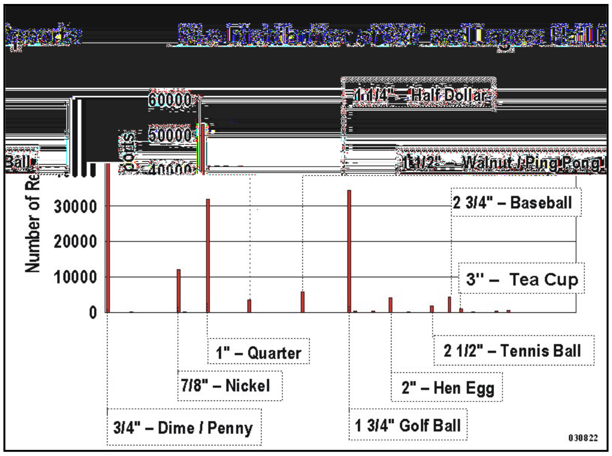


Figure 1: Size distribution of severe hail reports (1955 – 2002)

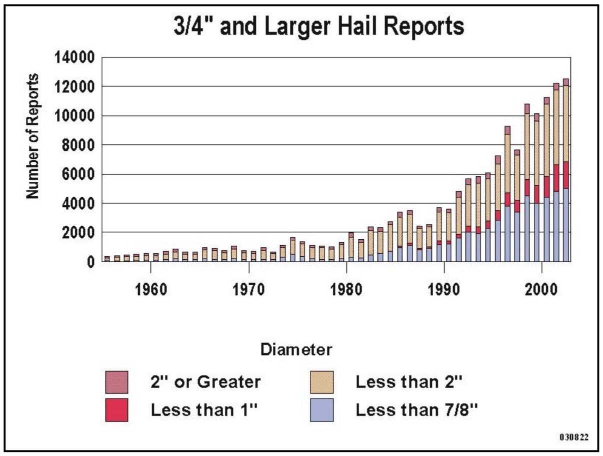


Figure 2: Growth of hail reports with time

reports. Further, 34% of the reports are of the smallest size (dime or penny) allowed. Extreme hail, stones 2" (51 mm) or greater, accounts for less than 10% (8.2%) of the reports.

Because hail size is typically only a subjective estimate, the question as to what is the largest hailstone ever recorded in the United States remains open. On June 22, 2003, a hailstone measured at 7 inches in diameter (18.75" in circumference) fell at Aurora, NE. This was compared to the "football" size hailstone that fell in Coffeyville, KS, September 3, 1970, with a measured diameter of 5.7 inches (17.5" in circumference) and declared to be a "record." However, the following report of a storm at Burr Oak, Noble County, Indiana, on the evening of May 6, 1961, appeared in *Storm Data* (National Climatic Data Center, 1961):

> *Large hail, golf ball to 10-inch diameter size, was reported.*

The quantization of hail sizes makes it extremely difficult to use existing routine data to determine record hail sizes.

3. CHARACTERISTICS OF THE DATA

The number of severe hail events reported each year (Fig. 2) gives some indications of the quality of the data. The number of reports has increased at a nearly exponential rate from less than 350 in 1955 to more than 12,500 in 2002. For individual years, deviations from the long-term trend are related to the seasonal synoptic pattern, e.g., the years 1987 and 1988 were unusually "quiet" severe weather years (Grenier et al, 1990). However, in general, the inflation in the number of reports is likely more a reflection of changes in society and the NWS reporting system than in the severe hail event climatology.

Societal changes can either increase or decrease the number of reports. Decreasing rural populations and expanding urban areas tend to exacerbate the under-reporting bias caused by a lack of available observers (e.g., Doswell, 1980). These trends tend to bias the number of reports towards populated areas. In contrast, Changnon's use of crop insurance losses tends to bias his presentations towards more rural, agricultural areas.

However, the integrated impact of societal trends is not that clear. Conflicting factors are active. For instance, the increasing availability of cell phone-type technology makes it much more likely that people will report a large hailstone that they find when they are away from their residence or business.

Operational procedures play a large role in determining the efficiency with which severe thunderstorms are reported (Kelly and Schaefer, 1982). The incomplete record for 1972, the year the method of archiving the data changed from using the USAF record to a direct encoding of *Storm Data*, is readily apparent, as only 65% of the expected number of severe hail observations was recorded.

These data show an important but indirect relationship between weather radar technology and observed hailstorm climatology. As weather radar improved, the number and quality of warnings increased. The increase in the number of warnings brings about an increase in the number of reports as the public is made aware that there is probably severe hail activity going on in their area. Also, the improved radar information permits the NWS to interrogate more specific locations for the occurrence of potentially severe weather.

Installation of the national network of WSR-57 10 cm radars began in 1959 (Whiton et al, 1998). Immediately after that, the steady increase in the annual number of severe thunderstorm wind events started. From 1976 through 1979, the NWS procured 5 cm radars to fill the "gaps" in the national network. The impact of these radars is seen in the "jump" in the number of reported hailstorms in 1980.

It is likely that the increase in hail reports during the mid-1980s is related to the implementation of the Radar Data Processor (RADAP) II on eleven NWS radar sites. RADAP II allowed the real time evaluation of vertically integrated liquid water (VIL). This was the first time that VIL (Greene and Clark, 1972), a good indicator of the presence of large hail, could be used in warning operations (Winston and Ruthi, 1986). The effect of the WSR-88D radar is even more dramatic. An increase of almost 1,400 severe hail reports was recorded between 1993 and 1995. During that year, 1994, forty-one of the Doppler radars were accepted by the NWS.

In October 1979, a proposed verification scheme for severe thunderstorm warnings was first presented (Pearson and David, 1979). The data showed that for the years 1977-1978, 94% of severe thunderstorm warnings failed to contain a reported severe storm. The NWS codified the basics of this verification methodology in the National Verification Plan (NWS, 1982). With the implementation of warning verification, local NWS offices found it advantageous to document severe thunderstorms that occurred within warnings and the annual average number of reported severe hail events jumped from about 1,100 in the late 1970s to almost 2,500 in the early 1980s.

During the first 19 years of the database, only 39 reports of nickel (or mothball) size hail were recorded (Fig. 3). Starting in 1983, hailstones of this size were reported with increasing frequency. By 2002, over 14% of severe hail reports were stones of this size. From 1985 through 1996, over 20% of the nickel size reports came from Oklahoma. This is a direct result of offices aggressively collecting verification data and asking observers to compare the size of the hail to coins.

4. GEOGRAPHIC DISTRIBUTION OF HAIL REPORTS

Even with the problems associated with the database, there is much information that can be obtained through an examination of geographic distribution of hail reports. The geographic distributions were constructed by tallying the number of hail reports in 2^{o} latitude by 2^{o} longitude "squares." The totals were then normalized by area and by year. To provide a degree of smoothing, values were computed at 1^{o} latitude and longitude increments across the contiguous United States. This process is the same as used by Kelly et al. (1978). Overlapping the squares process is equivalent (ignoring the modest error caused by the variance in area between adjacent 1^{o} squares) to smoothing 1^{o} square data with a running boxcar average. Such boxcar smoothing is less severe than that which results from using a Hann average. However, the boxcar method induces a slight phase shift in small-scale variations (Blackman and Tukey, 1958). The count of reports in each square is then normalized by the number of years in the database and by area in nautical miles. The data are then scaled so that reports per decade per 10,000 nmi^2 are plotted.

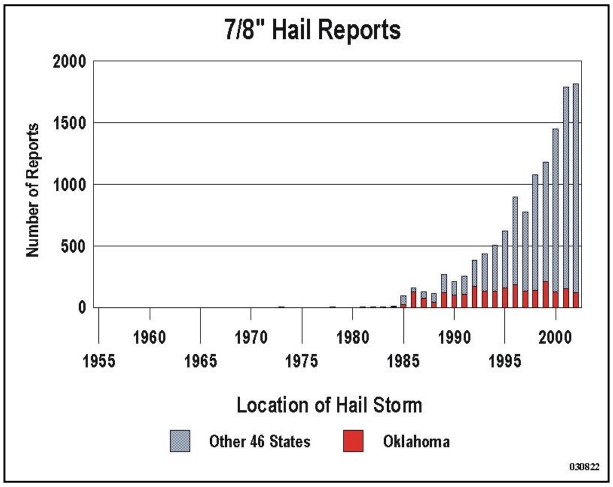
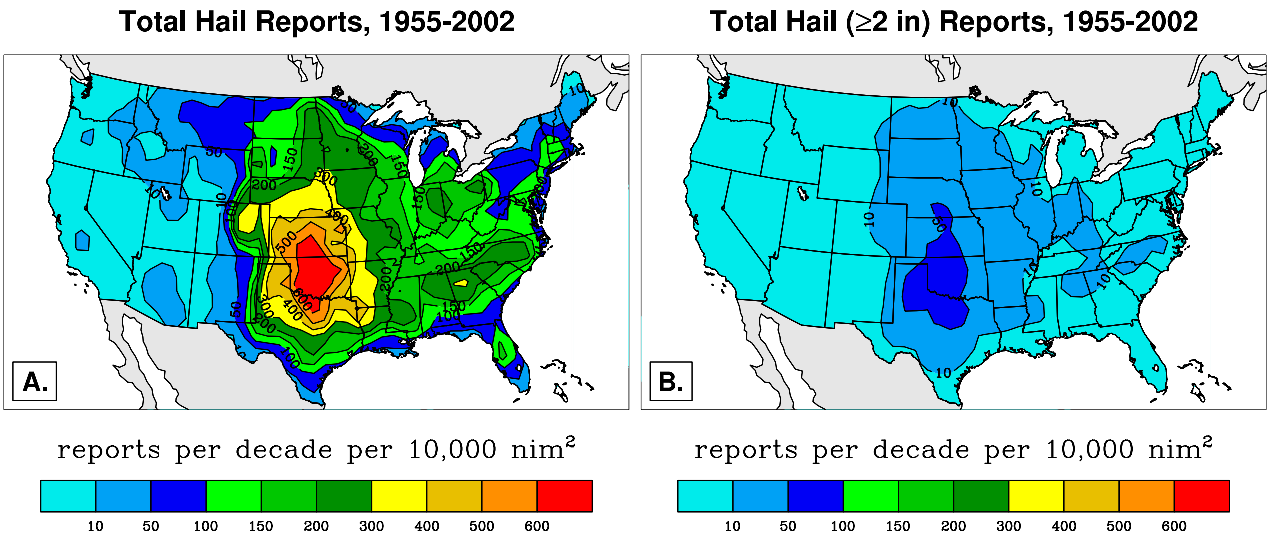


Figure 3: Nickel size hail reports

4.1 Annual pattern of United States severe hail events

The pattern of severe hail over the contiguous United States (Fig. 4A) shows a broad region of enhanced activity lying in a generally north-south belt


Total Hail Reports, 1955-2002

Total Hail (≥2 in) Reports, 1955-2002

Figure 4 (A-B): Geographic distribution of severe hail

that stretches from south central Texas to the Valley of the Red River of the North in North Dakota and Minnesota. Enclosed in this region is a large maximum of more than 600 severe hail reports per decade per 10,000 nmi^2 that covers most of Oklahoma. This area roughly corresponds to the so-called “tornado alley” region of the United States where strong “supercell” thunderstorms are prevalent during the spring months. The potential in this area for tornadic thunderstorms has been recognized since the 1930s (Court, 1970). This pattern reflects that large hail is typically a by-product of tornadic supercell storms. This general “springtime weather pattern” also produces severe convection in the form of mesoscale convective systems, squall lines, and derechoes which all have the capability of producing severe hail and contributing to the report database.

As is seen in Figure 2, there are fine scale details superposed upon this broadly defined region. There is an extension of the area of maximum reports southeastward across northeastern Texas (along the Red River of the South) which, ignoring a small break in eastern Mississippi, bows northeastward to North Carolina. A second area of enhanced hail activity lies in northeast Colorado in the old National Hail Research Experiment Area (Foote and Fankhouser, 1973). This pattern has general similarities to the “pattern of the Index of Potential Hail Damage to Property” that Changnon republished in 2002 (Fig. 5). The main difference compared to Changnon’s work is that the present analysis is displaced eastward so that the maximum is positioned over higher populated areas of Oklahoma, Kansas, and Nebraska. Similarly, Changnon’s eastward extension across Arkansas is displaced southward to lie over the more populated areas along the Red River.

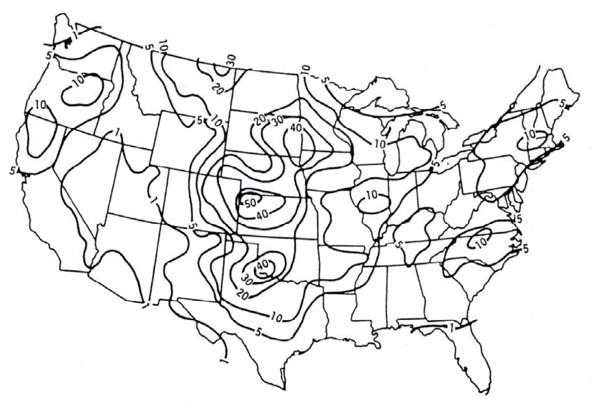


Figure 5: Index of potential hail damage to property (Changnon, 1978)

The chart of 2” and greater hail is similar to the severe hail. The maximum is reduced to between 60 and 100 severe hail reports per decade per 10,000 nmi^2. The southwest area of the maximum bulges westward to encompass the cities of Lubbock and Amarillo, TX. There is a zone of increased activity running north to south across middle Tennessee and central Kentucky that does not appear in the all-severe hail distribution.

4.2 *Seasonal variations in the geographic distribution of severe hail events*

To examine the variability of hail events throughout the year, charts of the average monthly number of events across the contiguous United States were constructed. During the winter, severe hailstorms are generally restricted to the Southeast. Most activity occurs in a band from east Texas to north Alabama (Fig. 6A and 7A.) Meteorologically, this is a reflection of the relatively cool temperatures across the continent, the general lack of moisture in the air anywhere but along the coast of the Gulf of Mexico, and the low sun angle that limits the area of insolation sufficient for thunderstorm development.

In April, the sun angle and length of daytime heating increases and moisture returns northward due to the strengthening of the Bermuda High. This, in concert with northward migration of the jet stream, shifts the maximum hail area to Oklahoma and the Red River Valley (Fig. 6B and 7B).

Continued northward progression shifts the July maximum to the Plains from eastern Colorado to northern Minnesota (Fig. 6C and 7C). There is also a weak summer maximum in smaller hail sizes over the desert southwest, indicating reports from hailstorms occurring with the North American monsoon. The northwestern states also have a small signal during this period, as extreme heating along the sloping terrain during the summer months helps to produce instability over this region leading to some severe hail producing storms.

A small July area of enhanced hail activity is also located in Central Florida in the area where the Atlantic and Gulf of Mexico sea breezes often interact. Over the rest of the Southeast, except for along the Appalachians, hail activity during the summer is suppressed by the warm troposphere.

In the autumn, the severe hail activity pattern is quite similar to the spring pattern (Fig. 6D and 7D). However, the occurrence rate is greatly diminished.

5. DISCUSSION

The distribution and occurrence of hail was analyzed using the SPC database from 1955 to 2002. Interestingly, nearly half (42%) of the 155,005 large hail reports in the database are of hail less than one-inch in diameter. This raises the question as to whether there is an over-reporting or under-reporting of hail.

Consider that golf ball size hail (1-3/4“) is the second most reported hail size. More golf ball size hail is reported than all larger sizes combined. Is significant hail of 2.00 inches in diameter or larger really that rare?

Hail reports tripled between the middle 1980s into 2000 with the onset of the WSR-88D and the aggressive verification program by the National Weather Service. Most hail is described by comparing it with the size of American coins, but there are none smaller than the size of a dime. Marble size hail used to be a popular description for marginal or non-severe hail; however, most marbles are 5/8-inch diameter (the shooter marble is 1.00 inch in diameter). Currently most non-severe hail is reported as ½-inch diameter.

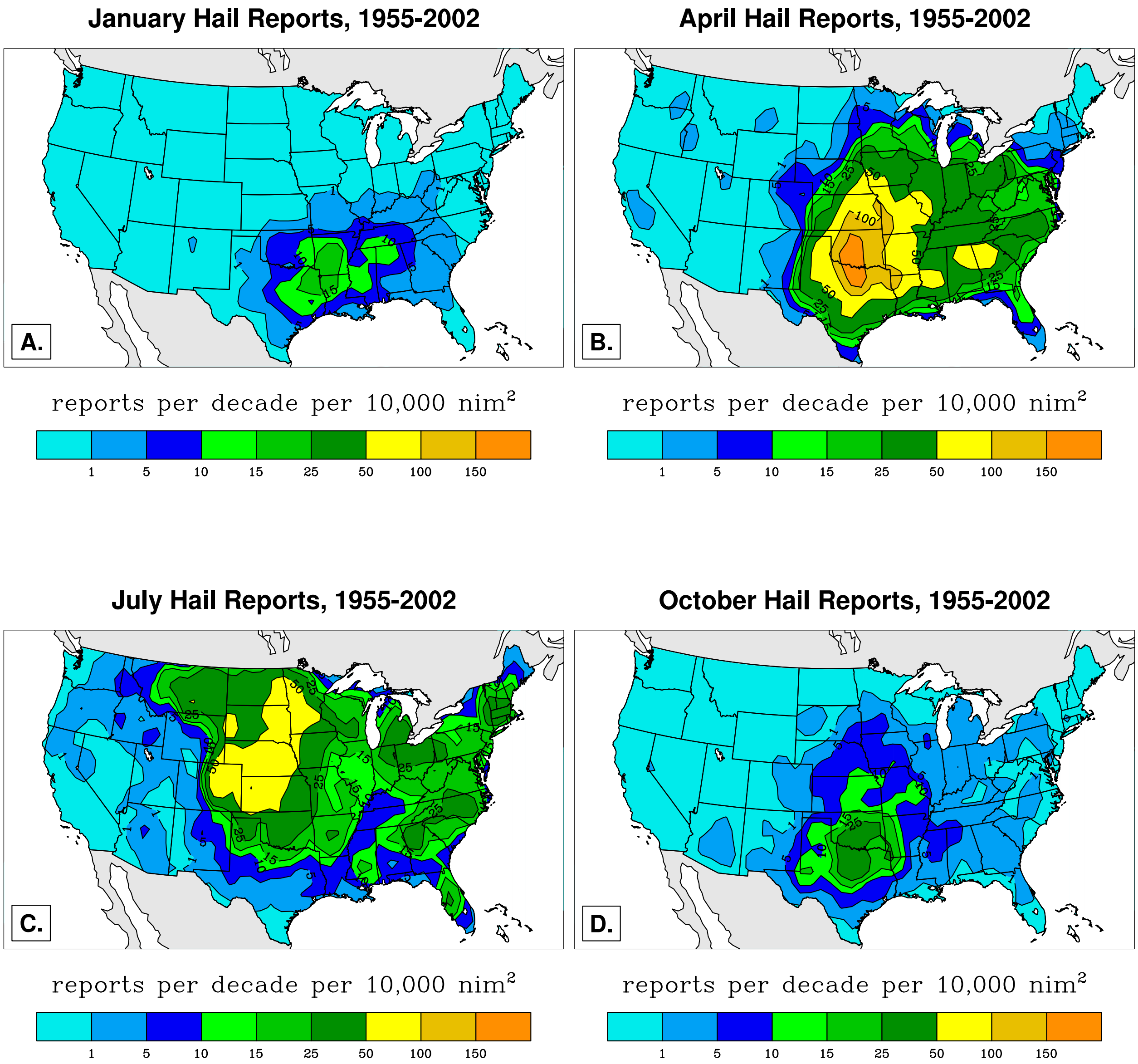
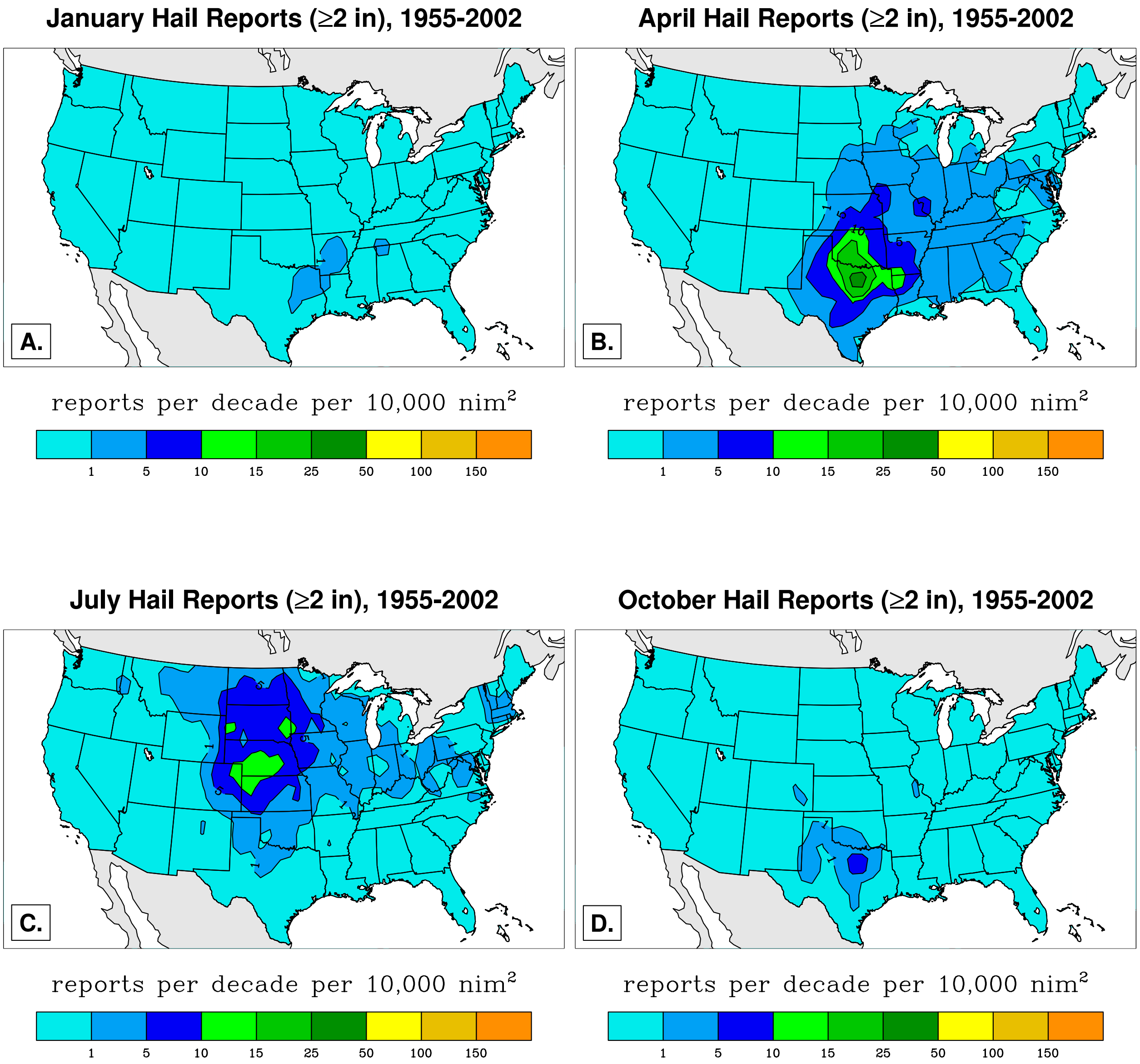


Figure 6 (A-D): Monthly distributions of severe hail events

Where does that leave the validity of hail reports? Most people, even storm chasers, do not use calipers to measure hail size. Also, if large hail is falling, a prudent observer is not going to risk injury by getting out of the car or stepping out of the house to measure, i.e., since 1955, the data shows six fatalities and 181 injuries. If the hail is not measured immediately, it is likely that some melting occurs when the observer waits until the hail stops to measure sizes.

Even though several problems exist with the hail report database, the observations are consistent with meteorological theory. Also, the seasonal and spatial consistencies between the all-severe hail (Fig. 6) and the extreme hail distributions (Fig. 7) give confidence that the reports in the database represent the general pattern of hail occurrence across the United States. A useful exercise for further study will be to compare this database with Stan Changnon's database that used hail sizes inferred from insurance databases.

In the future, we speculate that increases in the yearly number of hail reports will continue, due to increasing population, public awareness, and new technology (video, e-mail, cell phones). Additionally, new observing systems, such as dual polarization radar (Kennedy et al., 2001), will help forecasters more accurately discriminate between storms with and without hail. This technology can lead to improved hail reporting practices, as verification efforts (contacting potential observers, for example) can be focused on storms that are known to have a high likelihood of containing hail.


January Hail Reports (≥2 in), 1955-2002

April Hail Reports (≥2 in), 1955-2002

July Hail Reports (≥2 in), 1955-2002

October Hail Reports (≥2 in), 1955-2002

Figure 7: Monthly distribution of 2" or larger hail events

6. REFERENCES

Blackman, R.B., and J.W. Tukey, 1958: The Measurement of Power Spectra. Dover, New York NY, 190 pp.

Changnon, S.A., 1966: Note on Recording Hail Incidences. *J. Appl. Meteor.* , **5**, 899 – 901.

Changnon, S.A., 2002: *Climatology of Hail Risk in the United States, Technical Report CRR-40*. Changnon Climatologists, Mahomet, IL, 67 pp.

Changnon, S.A., 1999: Data and approaches for determining hail risk in the contiguous United States. *Appl. Meteor.*, **38**, 1730 – 1739.

Court, A., 1970: *Tornado Incidence Maps, ESSA Technical Memorandum ERLTM-NSSL 49.* National Severe Storms Laboratory, Norman, OK, 1970, 75 pp.

Doswell, C.A. III, 1980: Synoptic-scale environments associated with high plains severe thunderstorms. Bull. Amer. Meteor. Soc., **61**, 1388 – 1400.

Foote, G.B., and J.C. Fankhouser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm, *J. Appl. Meteor.,* **12**, 1330 – 1353.

Greene, D.R., and R.A. Clark, 1972: Vertically integrated liquid water: a new analysis tool. *Mon. Wea. Rev.*, **100**, 548 – 552.

Grenier, Leo, and J.T. Holmstead, 1986: Severe Local Storm Verification Preliminary Procedures, *NOAA Technical Memorandum NWS NSSFC - 12*, National Weather Service, Silver Spring, MD, 10 pp.

_____, _____, and P.W. Leftwich Jr., 1990: Severe Local Storm Verification: 1990, *NOAA Technical Memorandum NWS NSSFC - 27*, National Weather Service, Silver Spring, MD 20910, 22 pp.

Kelly, D.L., and J.T. Schaefer, 1982: Implications of severe local storm warning verification, Preprints, *12th Conference on Severe Local Storms,* San Antonio, TX, Amer. Meteor. Soc., 459 – 462.

Kelly, D.L., J.T. Schaefer, R.P. McNulty, C.A. Doswell III, and R. F. Abbey, 1978: An augmented tornado climatology, *Mon. Wea. Rev*., **106,** 1172 – 1183.

Kennedy, P.C., S.A. Rutledge, W.A. Petersen, V.N. Bringi, 2001: Polarimetric radar observations of hail formation, *J. Appl. Meteor.,* **40**, 1347 – 1366.

Winston, H.A. and L.J. Ruthi, 1986: Evaluation of RADAP II severe-storm-detection algorithms, *Bull. Amer. Meteor. Soc.,* **67,** 145 – 150.

National Climatic Data Center, 1961: *Storm Data*, **3**, No. 5, p 40.

National Weather Service, 1982: *National Verification Plan*, U.S. Dept. of Commerce, NOAA, Silver Spring, MD, 81 pp.

National Weather Service, 2003: *National Weather Service Instruction 10 - 1605*, U.S. Dept. of Commerce, NOAA, Silver Spring, MD, 15 pp.

Pearson, A.D., and C.L. David, 1979: Tornado and Severe Thunderstorm Verification, Preprints, *11th Conference on Severe Local Storms*, Kansas City, MO, Amer. Meteor. Soc., 567 – 568.

Schaefer, J.T., and R. Edwards, 1999: The SPC Tornado/Severe Thunderstorm Database, Preprints, *11th Conference on Applied Climatology*, Dallas, TX, Amer. Meteor. Soc., 215 – 220.

Whiton, R.C., P.L. Smith, S.G. Bigler, K.E. Wilk, and A.C. Harbuck, 1998: History of operational use of weather radar by U.S. Weather Services. Part 1: the pre-NEXRAD era. *Wea. Forecasting*, **13**, 219 – 243.