MET 4410 Remote Sensing: Radar and Satellite Meteorology
MET 5412 Remote Sensing in Meteorology

Lecture 16: Meteorological Targets of Radar: Clouds, Rain, Z-R relationship, Snow, Bright-band, and Hail

Clouds

- Clouds include **precipitating** and **non-precipitating clouds**. Here we are talking about **non-precipitating clouds**. Precipitating clouds are included in the "Rain" section a few slides later.
- Non-precipitating clouds are usually not detectable by precipitation radars in S & C bands (wavelengths are in centimeters)
- Non-precipitating clouds are detectable by cloud radars in W band (wavelengths are in milli-meters).
- **Particles in non-precipitating clouds are small (diameter ranging from 10 to 100 micrometer), including** very small liquid water droplets (5-50 micrometers) and ice crystals (10-100 micrometers).

Clouds Drop Size Distributions (DSDs)

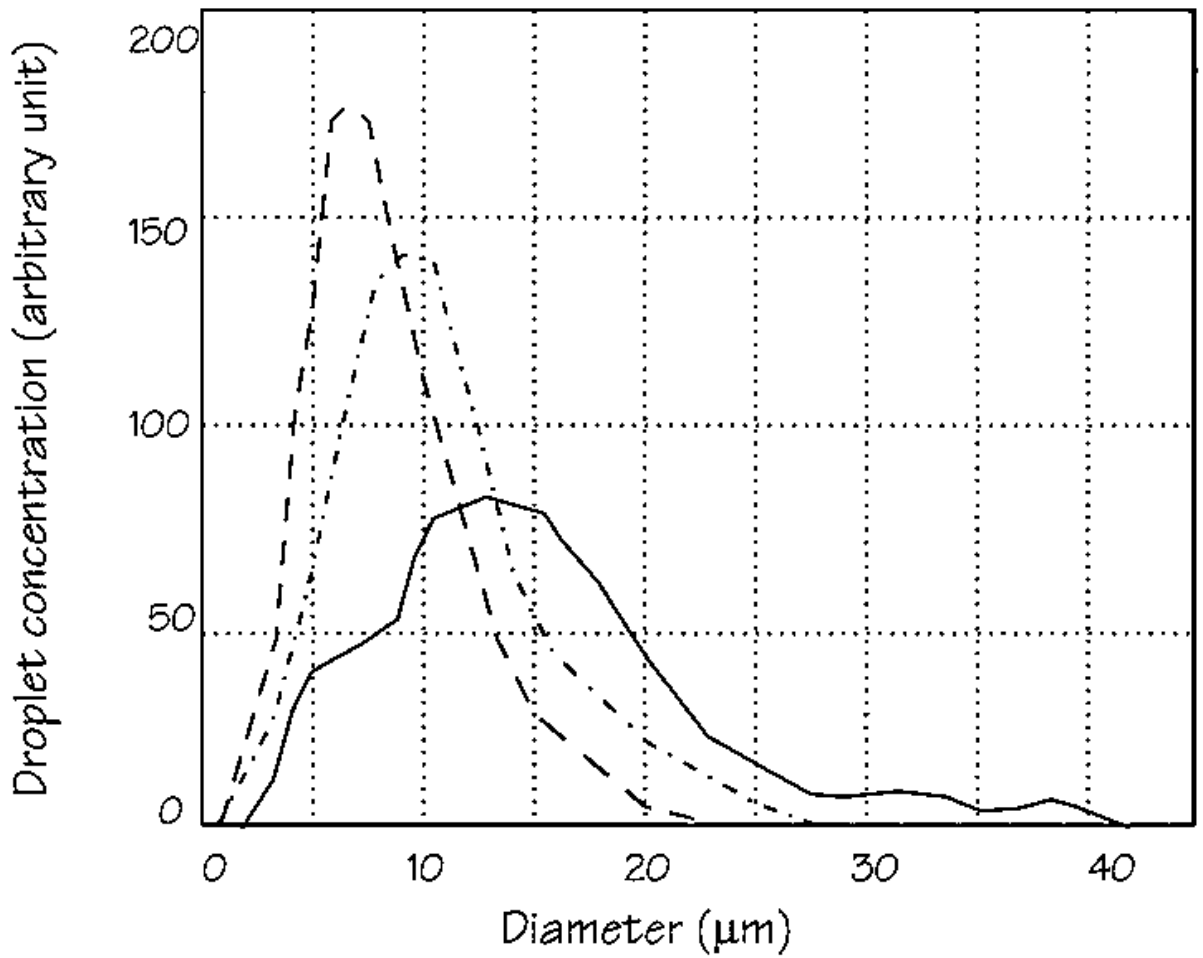


Fig. 8.1 The mean drop size distributions for various cloud types. Cumulus congestus (solid); altostratus (dash-dot-dash); Stratus (dash). Based on Feltcher, 1966.

Calculate Radar Reflectivity Factor from DSD

$$z = \sum N_i D_i^{\,6}$$

Table 8.1 Contribution to radar reflectivity factor by each individual cloud droplet size. Size spectra is based on the continental type cloud of Fig. 8.1.

Dia (μm)	No./cm³	$N D^6$ (mm⁶/m³)
5	100	$1.56 \cdot 10^{-6}$
10	100	$1.00 \cdot 10^{-4}$
15	50	$5.69 \cdot 10^{-4}$
20	25	$1.60 \cdot 10^{-3}$
25	10	$2.44 \cdot 10^{-3}$
30	5	$9.19 \cdot 10^{-3}$
35	1	$4.01 \cdot 10^{-3}$
	Total =	$1.80 \cdot 10^{-2}$ mm⁶/m³
		= -17.4 dBz

The contribution to reflectivity from the small droplets, even though they outnumber the larger drops by one or more orders of magnitude, is generally negligible. Most of the reflectivity comes from the largest droplets. This is due to the sixth power term.

Rain

- Rain is produced by **precipitating clouds**.
- Rain can come in a wide range of intensities, from light drizzle to downpours in severe thunderstorms
- Rain and precipitating clouds are very easily detected by most radars. The best type of radar to detect rain is precipitation radar in S & C bands (wavelengths are in centimeters).
- **Particles in precipitating clouds** includes *snowflakes* above the melting level & *raindrops* below the melting level. There also could be *graupel and hailstones* in precipitating clouds .
- **Precipitation-sized particles in rain and precipitating clouds are larger than cloud-particles. Diameter size:**
  - Drizzle droplets: about 100 micrometer
  - Raindrops and graupel: 0.1-3 mm
  - Snowflakes: >0.1 cm
  - Hailstone: > 5 mm

Rain DSD

- How to sample Rain DSD: Camera photographing, then measure the diameter of each individual raindrop.
- From DSDs, rainrate (R, mm/h), liquid water content (M, g/m^3), and radar reflectivity (z, mm^6/m^3) are easily calculated.

Liquid water content:

$$M = \frac{\pi}{6}\int_0^\infty N(D)\rho D^3 dD = \frac{\pi}{6}\sum N_i \rho D_i^3$$

where ρ is the density of liquid or ice particles

Rain rate and radar reflectivity computed from DSD

Rain rate: $$R = \int_0^\infty N(D)V(D)D^3 dD = \sum N_i V_i D_i^3$$

Radar Reflectivity: $$z = \int_0^\infty N(D)D^6 dD = \sum N_i D_i^6$$

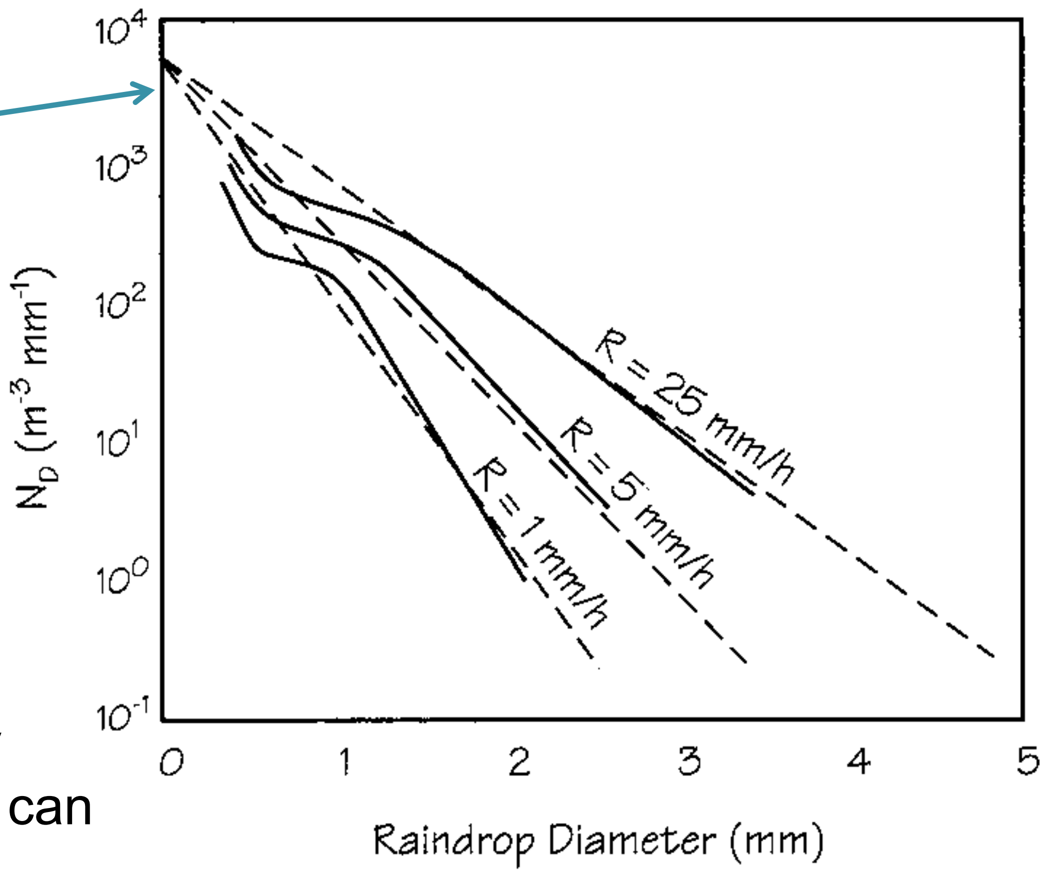
- where V(D) is the terminal fall velocity of raindrops, which is approximately proportional to $D^{0.5}$ to D^1 for raindrops and frozen hydrometeors depending on their sizes and habits, etc. (Rodgers and Yau 1989; Pruppacher and Klett, 1997).

An Empirical Rain DSD Equation: Marshall-Palmer DSD

$$N_d = N_0 e^{-\lambda D}$$

- where N_0=8000/(m^3 mm). *D* is drop diameter (mm). N_d is the number of raindrops

$$\lambda = 4.1 R^{-0.21}$$



- Where R is rainrate in mm/h.
- DSD can be obtained for any specific rain rate. Reflectivity can be derived from DSD.

Z-R Relationships

Using experimentally measured DSD to determine the empirical power-law Z-R relationship:

$$z = AR^b$$

where z is the radar reflectivity factor (mm^6/m^3), R is rain rate (mm/h), and A and b are empirical constants.

Marshall-Palmer Z-R relationship:

$$z = 200R^{1.6}$$

Z-R relationships are different for different meteorological conditions.

Snow

- “Why radar doesn’t detect snow very well?”

Reason 1: Precipitation rate for snow is usually much less than that for rain.

--Water equivalent precipitation rate of snow is less because under cold temperature, the maximum amount of moisture in the atmosphere is much less than that in warm temperature.

Snow

- "Why radar doesn't detect snow very well?"

Reason 2: Refractive indices of water and ice are very different.

For water: $|K|^2 = 0.93$

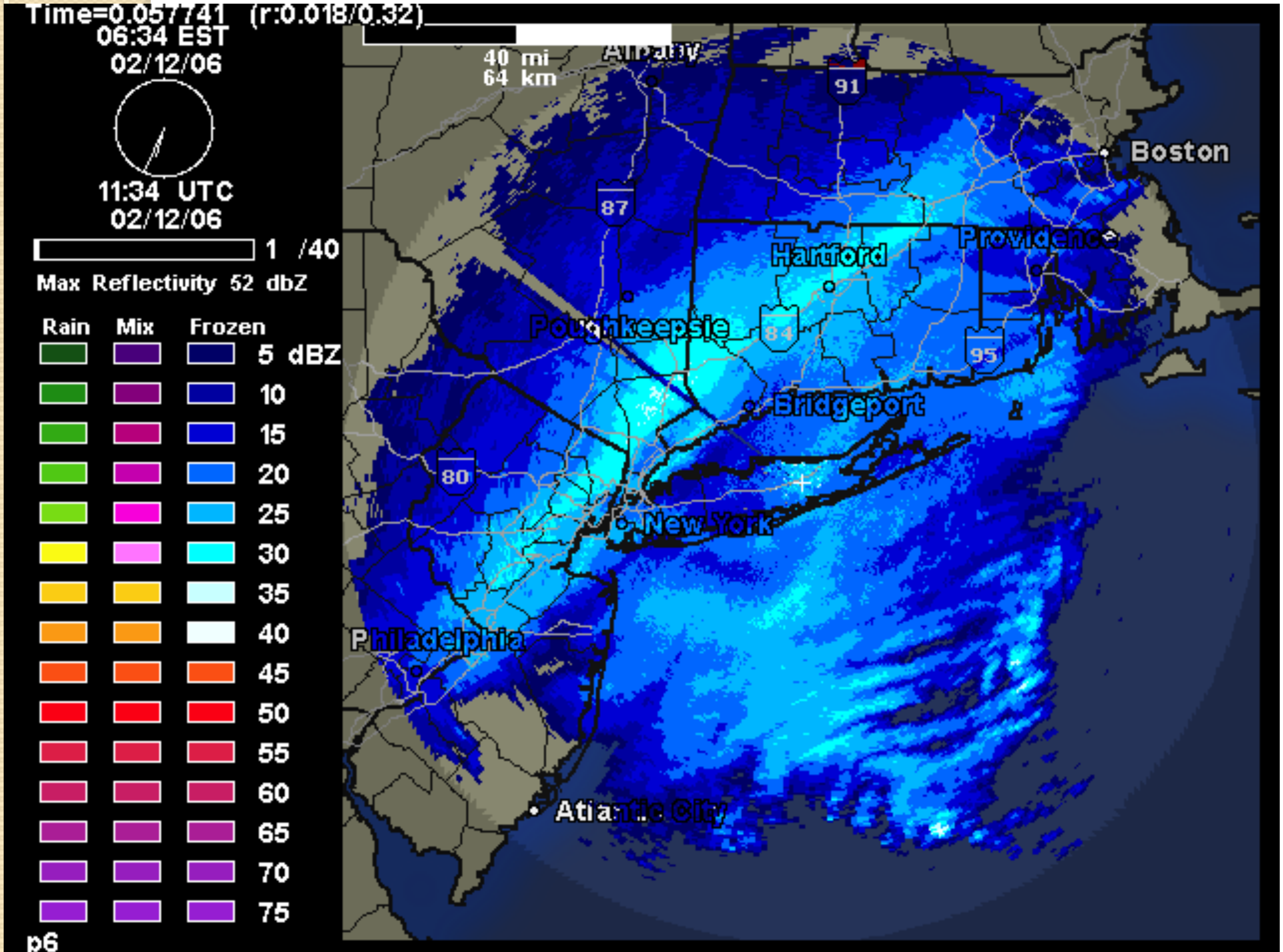
For ice: $|K|^2 = 0.197$

In radar equation:

$$p_r = \frac{\pi^3 p_t g^2 \theta \varphi h |K|^2 z}{1024 \ln(2) \lambda^2 r^2}$$

Therefore, the power received back from snow and ice is about 7 dB less than it would be if a radar were looking at liquid precipitation. So reflectivity for snow is smaller rain.

Northeast Snowfall on 02/12/2006



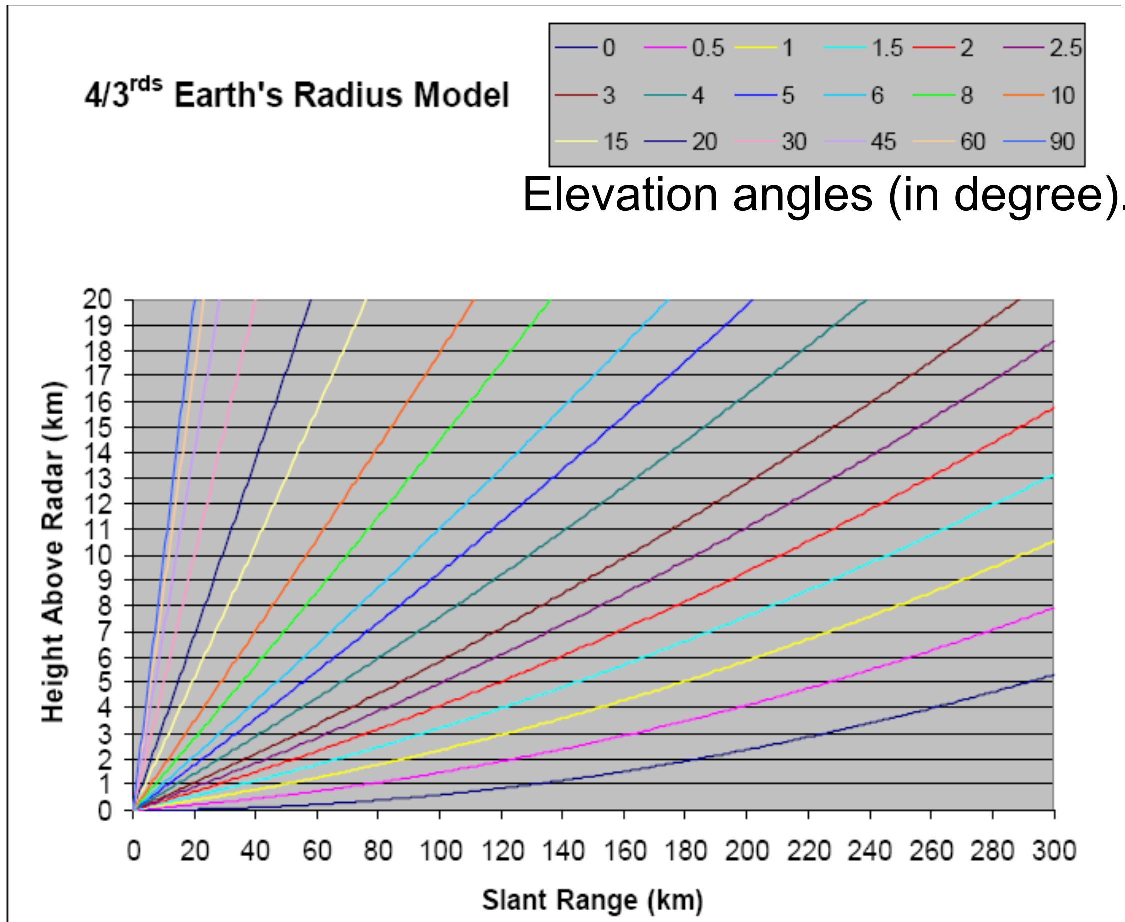
Low reflectivity values for snow: ranging between 5-30 dBZ

Snow

- "Why radar doesn't detect snow very well?"

Reason 3: Snow storms are often widespread, but shallow. So the radar beam might miss it.

- For example, a common snow storm with height of 1.5 km would be below the radar beam at distances beyond 120km (assuming standard refraction and a radar elevation angle of 0.5 deg) and radar can't detect.



Bright Band

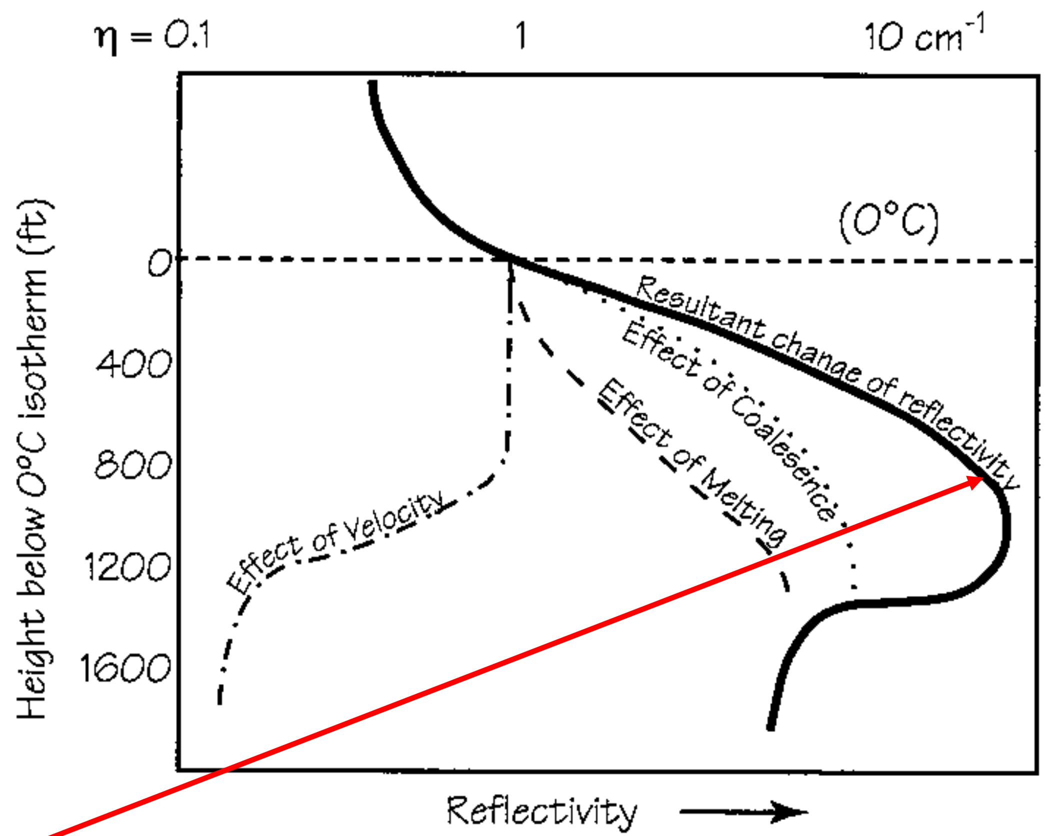
- **Background:** Precipitations could form through either a warm rain process or a cold rain process. A warm rain process produces precipitation through collision–coalescence between liquid particles. A cold rain process involves freezing and rain that falls to the ground begins as ice or snow above the melting level.
- **Definition:** A bright band is an enhancement of radar reflectivity at the **melting level** when snowflakes falling from above aggregate and develop wet surfaces.
- Bright bands only occur within cold-rain processes at the melting/freezing level (**0**℃ **level, which is about 5 km above the ground during summer & 1-2 km in winter in mid-latitude**).
- Bright bands occur primarily during stratiform or stable situations. In strong convection, bright bands are undetectable most of time because the transition between snow and rain is often so chaotic.
- During the decaying portions of thunderstorms, bright bands will be often detected.
- Overestimation of precipitation rate could occur due to the bright band contamination

Why do Bright Bands form?

- Reason 1: reflectivity: water>snow
- Reason 2: Fall speed difference
    - Fall speed (terminal velocity) of particles: Depends on particle's shape and density, as well as the density and viscosity of the atmosphere. Spheres fall faster than rough-shaped particles; Dense particles fall faster than light particles; Particles high in the atmosphere fall faster than near the Earth's surface (air density effect).
- Reason 3: At melting level, snow starts to melt from outside and form a water-coating, large, and irregular-shaped particle. To radar, dBz increases 7dBZ.
- Reason 4: particle size increases by coalescence.

How do Bright Bands form?

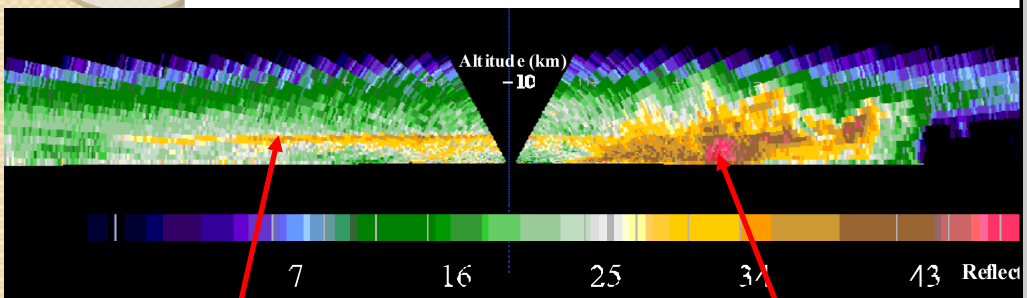
- Effect of velocity (fall speed) increasing: Reflectivity will decreases
- Effect of snow particle size reduce:: reflectivity will decrease
- Effect of melting: reflectivity will increase
- Effect of coalescence: reflectivity will increase



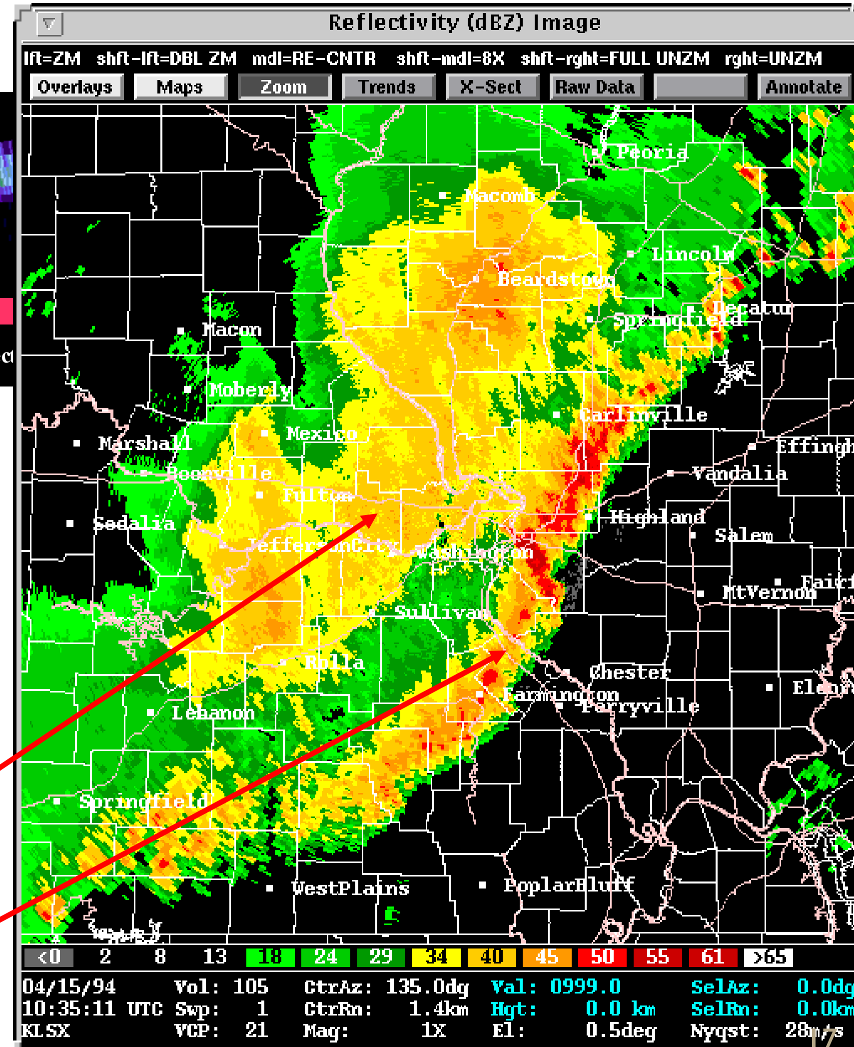
Collective Effect: Final resultant change of reflectivity: large increase below the melting level (0℃ height) mainly due to effects of melting & coalescence.

Bright Bands on Radar Vertical Image

Vertical cross section of radar reflectivity in a squall line



Horizontal radar reflectivity image of the same squall line



Bright band indicating stratiform precipitation regions

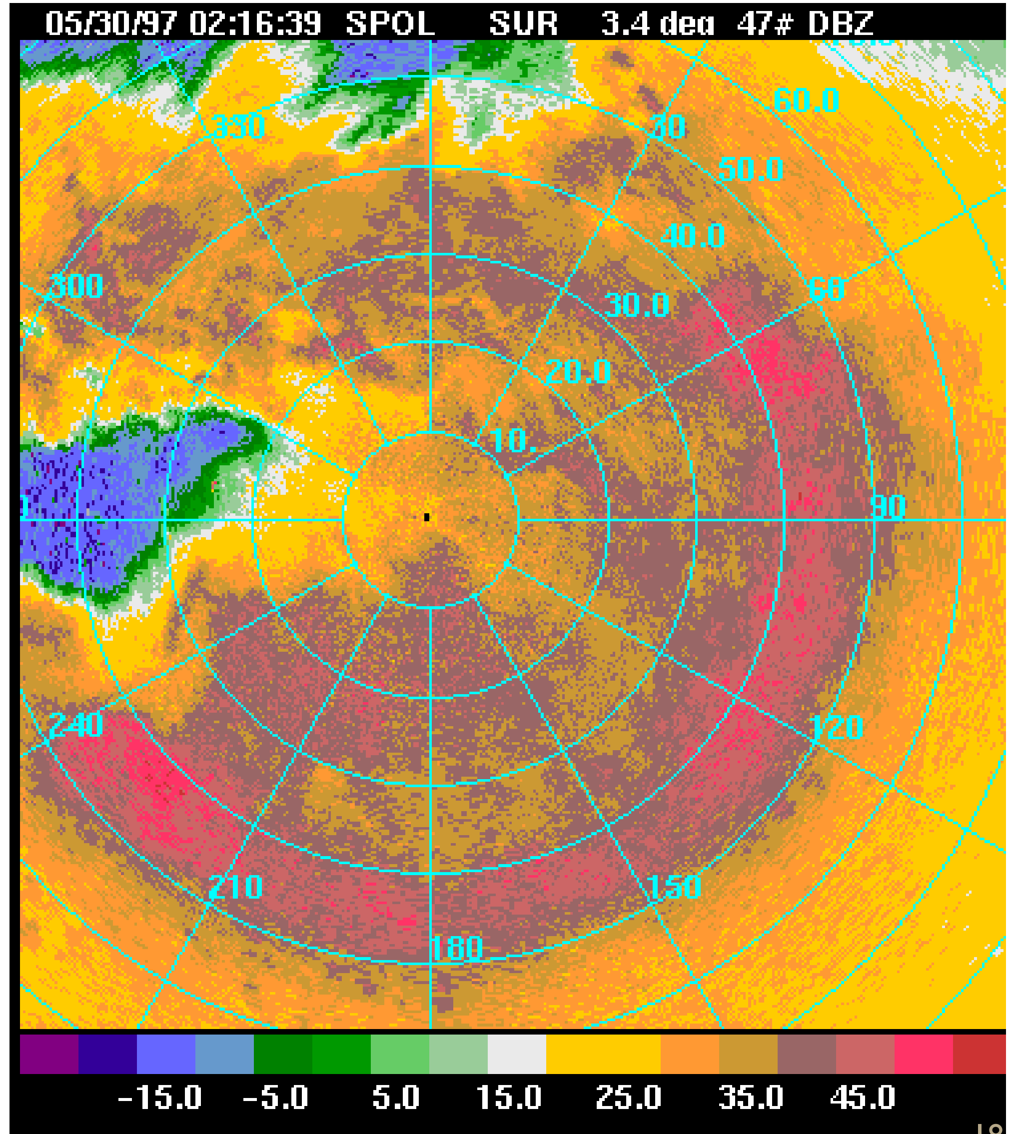
Convective Region without bright bands

Stratiform precipitation regions

Convective precipitation Region

Bright Band on Radar PPI Image

- The enhanced half-circle ring with 45-50 dBZ reflectivity is the bright band.
- Since the antenna elevation angle is 3.4 deg in this case, the echo height at 40-50 km distance is located at the melting level.
- Cases like this could cause overestimation of precipitation rate due to the bright band contamination when using Z-R relationship to estimate rain.



Hail

- Definition: Hail is defined as precipitation in the form of ice that has a diameter of at least 5 mm.
- Hail ranges from 5 mm to about 10 cm in diameter.
- Hail occurs almost always in thunderstorms, but can fall from rainstorms too.
- 85 % of all thunderstorms contain hail at least during part of their lives.

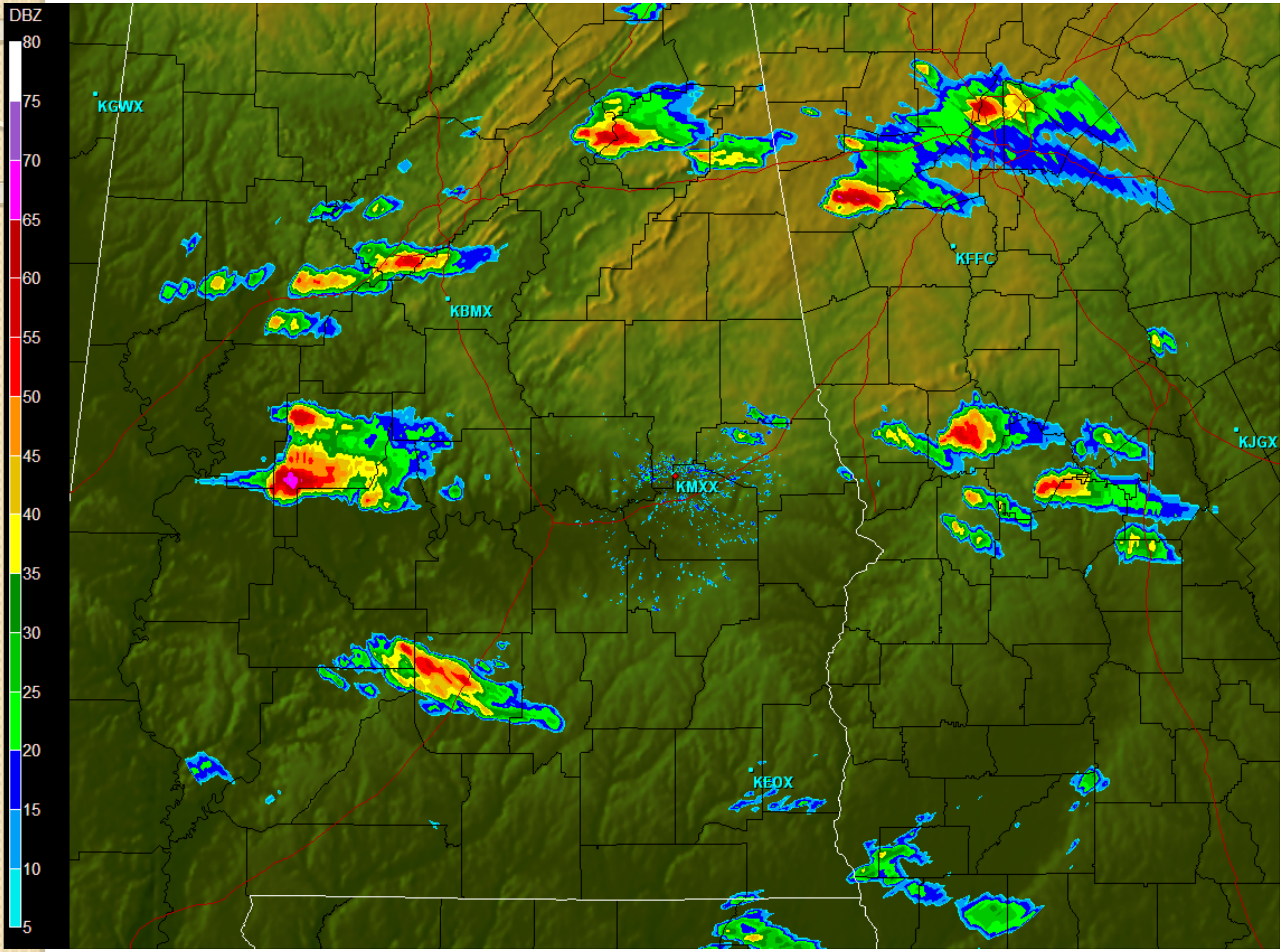
Detection of Hail by Conventional Radar

- **Reflectivity of Rain:** usually 20-50 dBZ (sometime could go up to 55 dBZ)
- **Reflectivity of Hail:** a general rule:
  - reflectivity>= 60 dBZ, definitely hail; 50-55 dBZ, possible hail; >=70 dBZ, large hail.
- **Uncertainties:**
  - Wet hails has greater reflectivity values than dry hails at the same size.
  - Almost all hailstones are in Mie region for 3-cm and 5-cm radars. For 10-cm radar, small hail is in Rayleigh region, but large hail is in Mie region
- **A flare echo** (sometimes called a "hail spike") is an artifact that sometimes appears on images of radar reflectivity when large hail is present in severe thunderstorms.

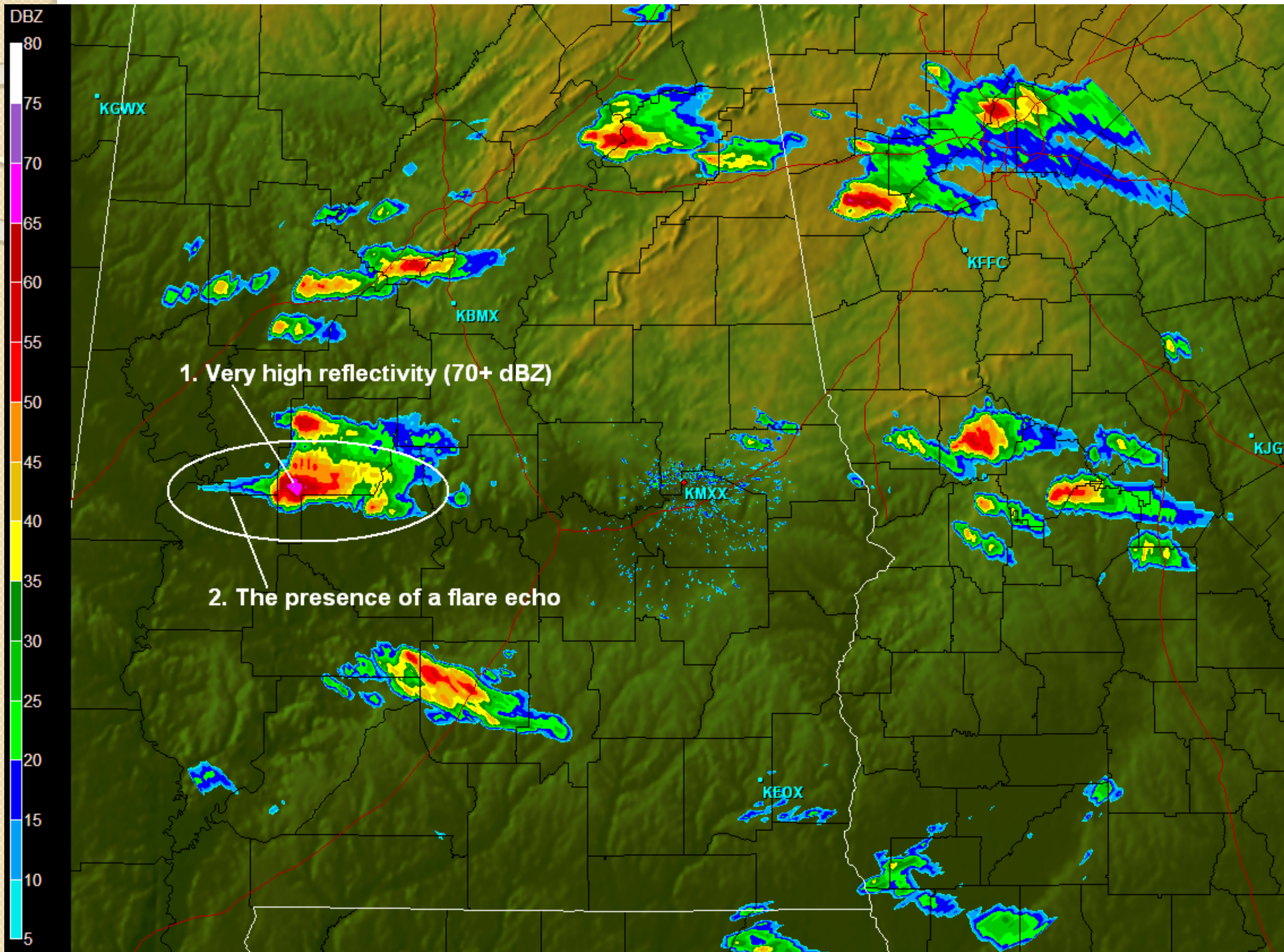
How does a Flare Echo occur?

- Radar transmitted microwave radiation is *strongly* scattered in all directions, by large hail.
- Some of the energy initially scattered by large hail hits the ground, and, in turn, is back-scattered. Some of the energy back-scattered by the ground strikes large hail within the storm.
- This back-scattered signal from the ground is still sufficiently strong that large hail back-scatters some of the energy to the radar.
- This weaker signal arrives a bit later than the initial strong signal of back-scattered energy, so the radar interprets this second signal as a weak, elongated echo (which meteorologists refer to as a flare echo).

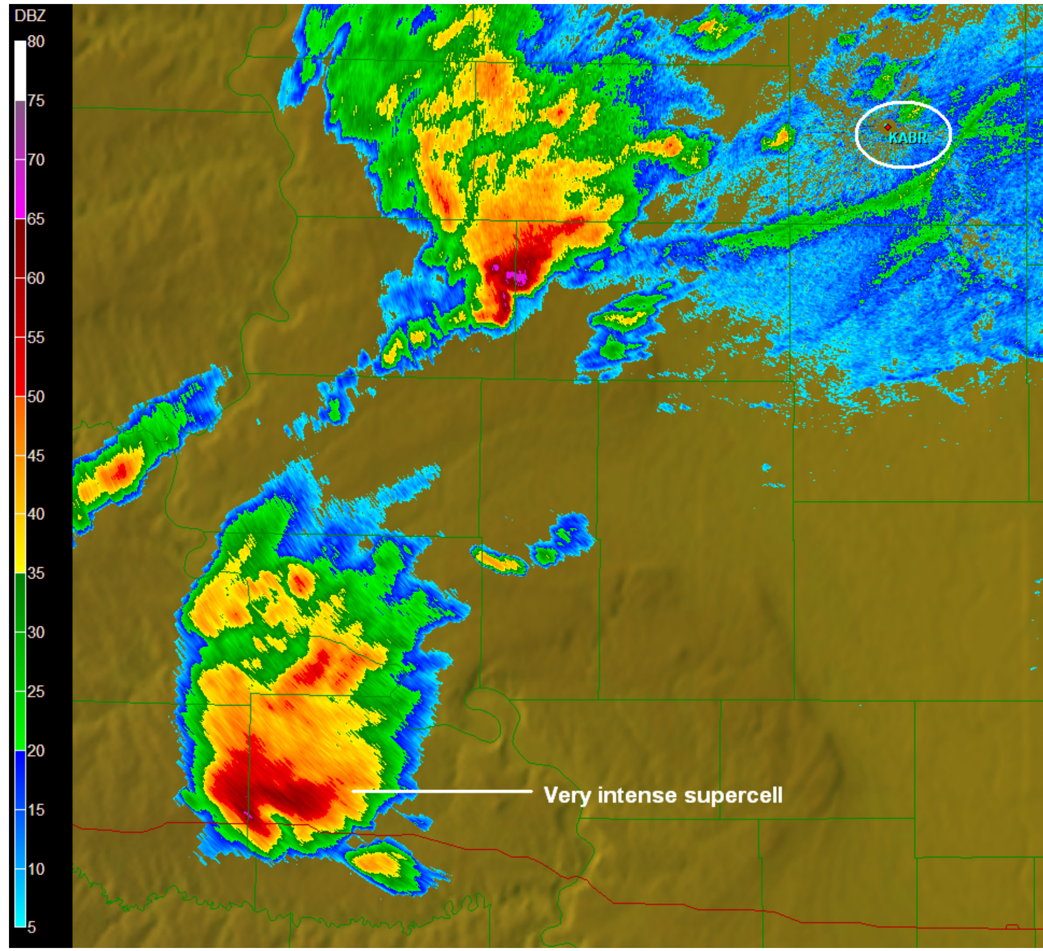
Which echo is likely to producing large hail?



Answer:


DBZ
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
KGWX
KBMX
KFFC
KJGX
KMXX
KEOX
1. Very high reflectivity (70+ dBZ)
2. The presence of a flare echo

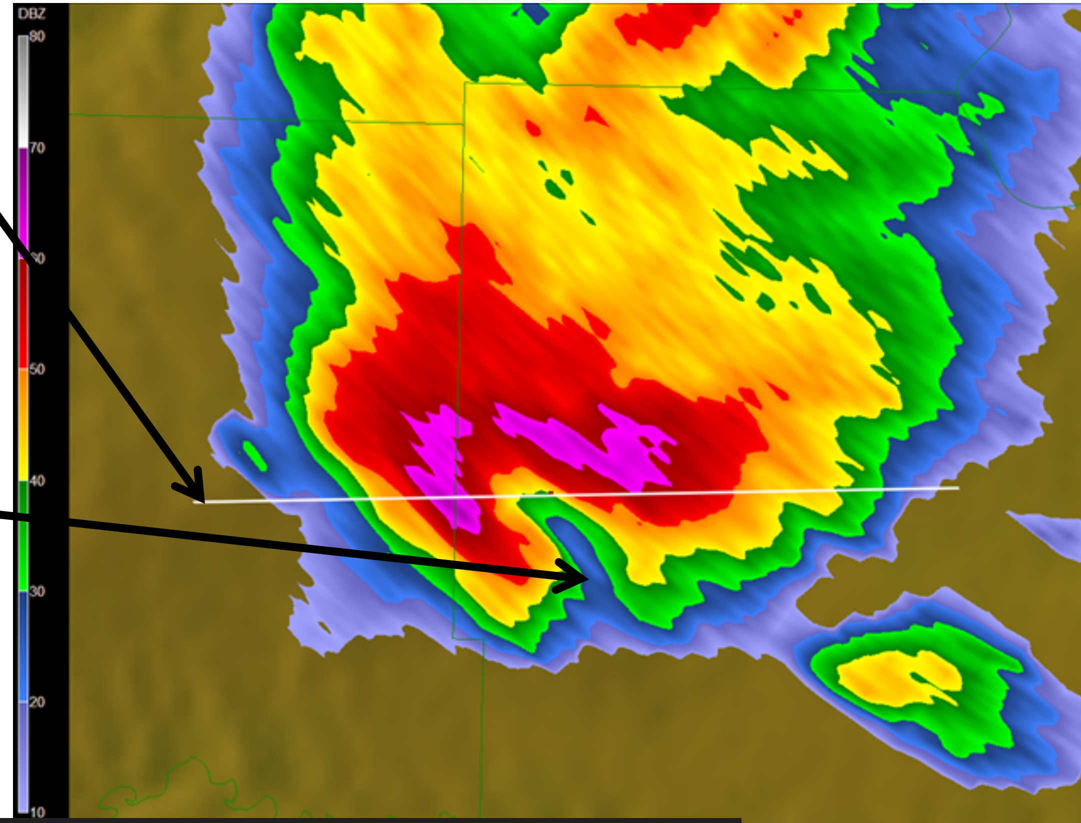
Severe thunderstorms over South Dakota, July 23, 2010



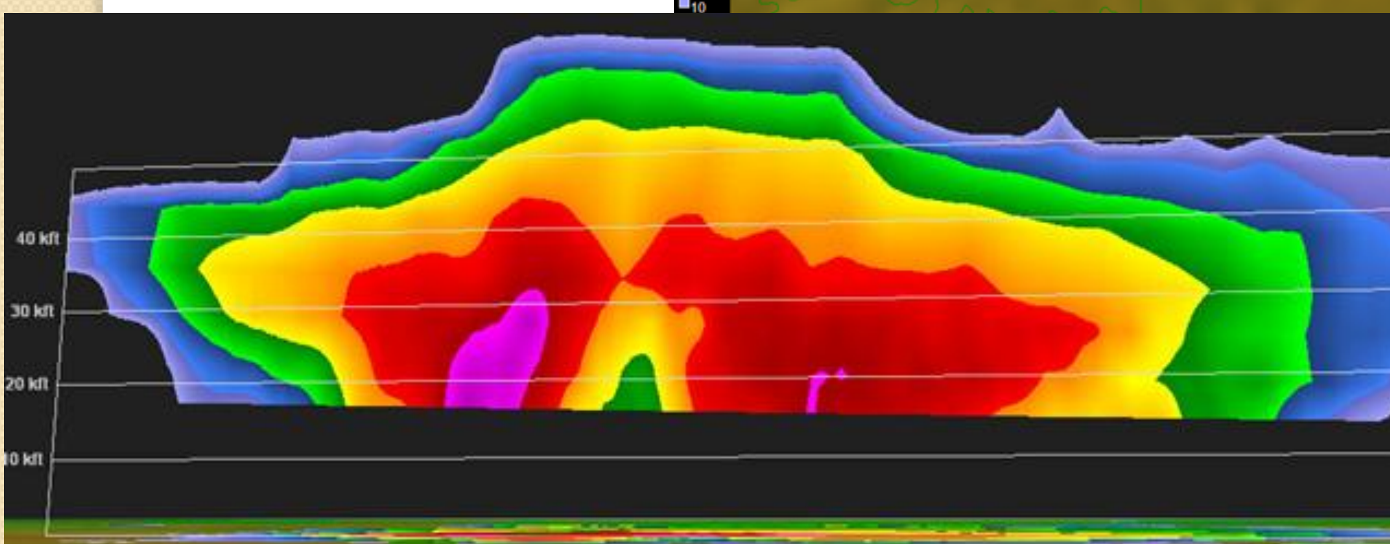
The giant hailstone that fell from a supercell at the town of Vivian, South Dakota, on July 23, 2010, had a record-breaking diameter of eight inches.

Cross-section along this line

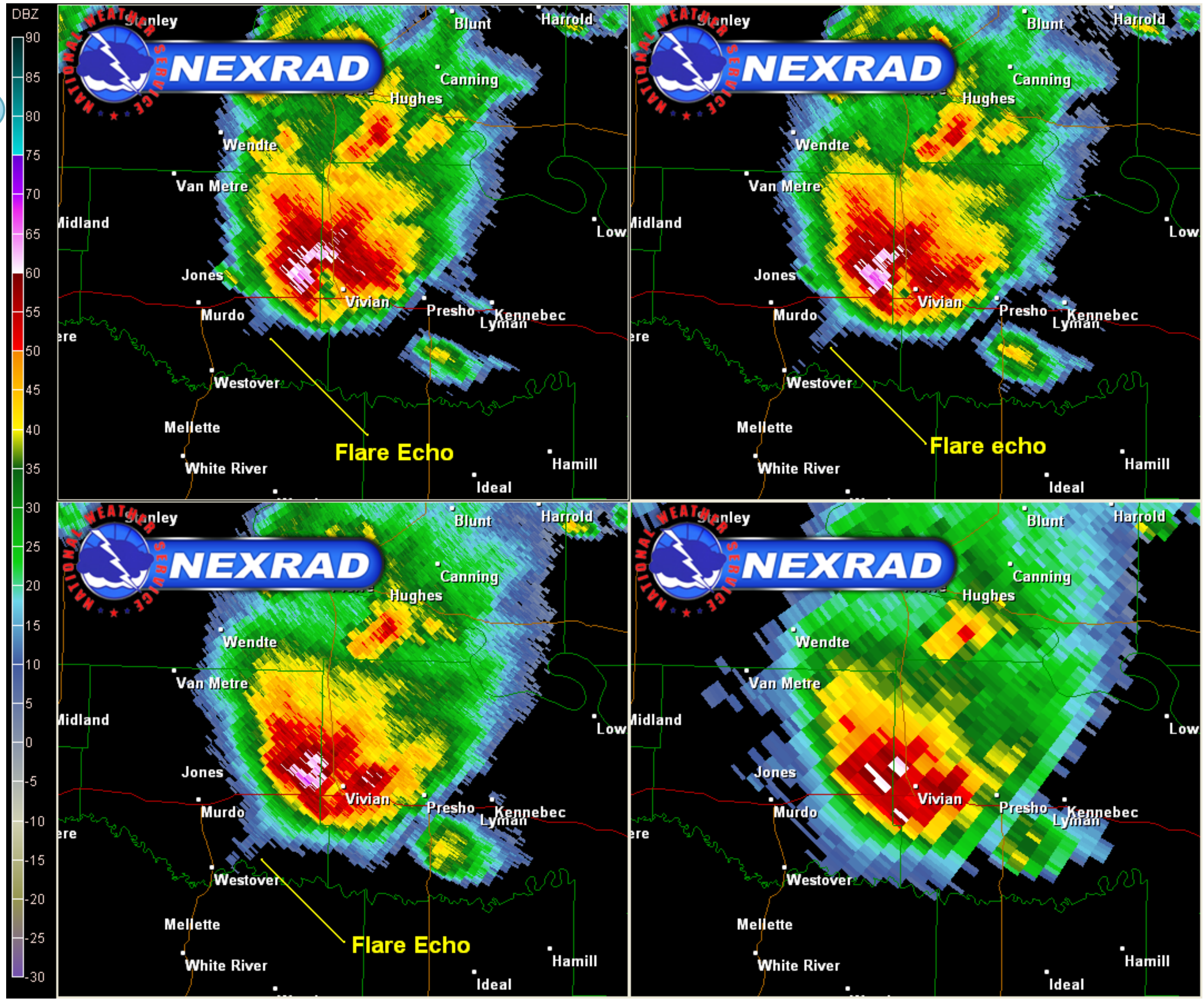
Hook Echo



Cross section



Radar images at Aberdeen SD around 23Z on July 23 (0.5, 0.9, 1.3, 1.8 degree elevation angles)



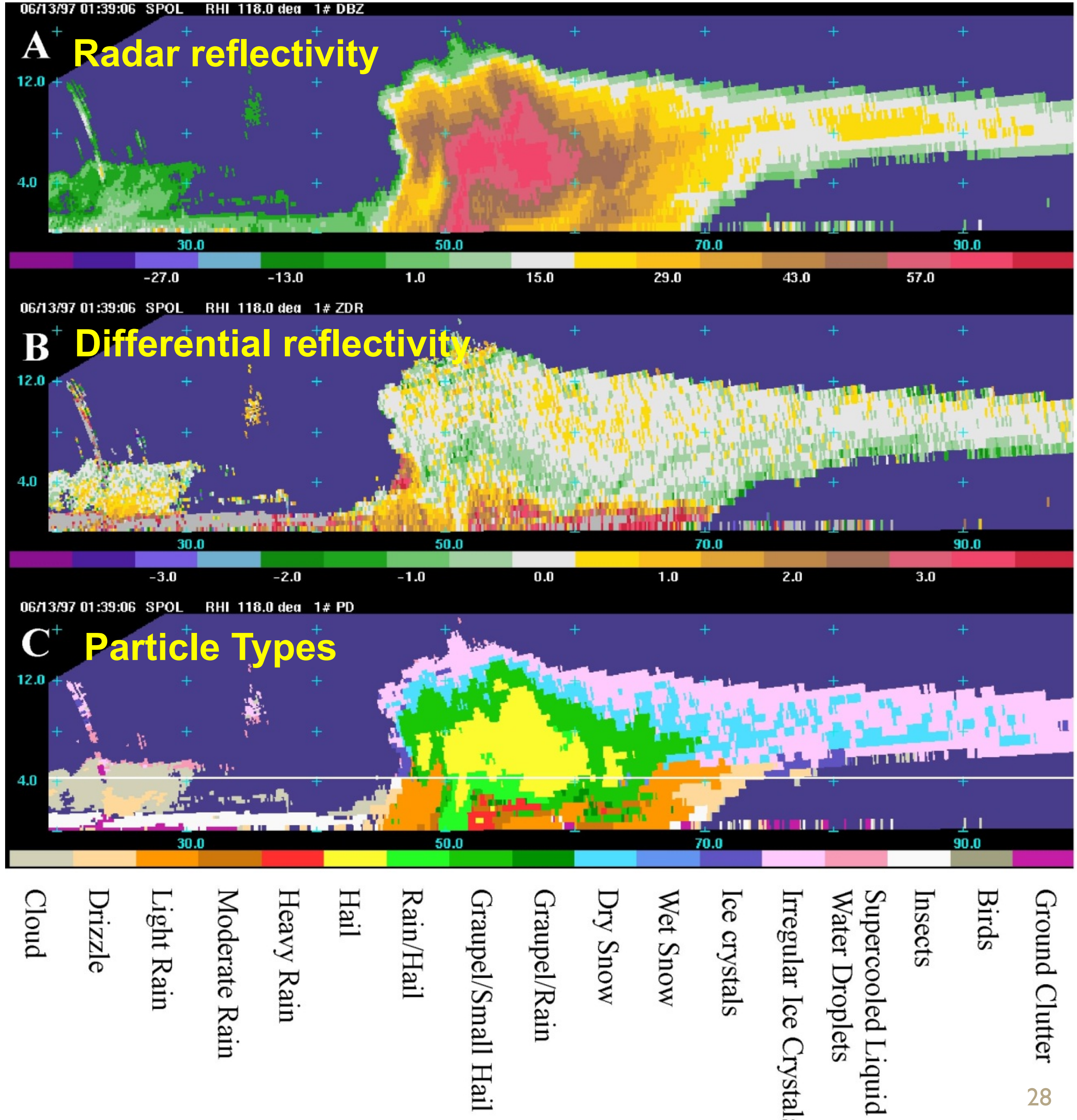
Dual-Polarization (Dual-Pol) Radar

- **Convectional radar** can not determine hail exactly
- **Dual-pol radar** will improve warnings for hail. Dual-pol radars are capable of distinguishing regions of hail from regions of heavy rain. They measure many parameters related to the polarization state of the transmitted and received radar energy. The set of measurable quantities that can be derived from polarization diversity radars together can be used to discriminate the types of particles (hail, rain, snow, small ice crystals, etc.) within a storm.
- **NWS is upgrading its Doppler radar network (WSR-88D)** to include dual-polarization function.

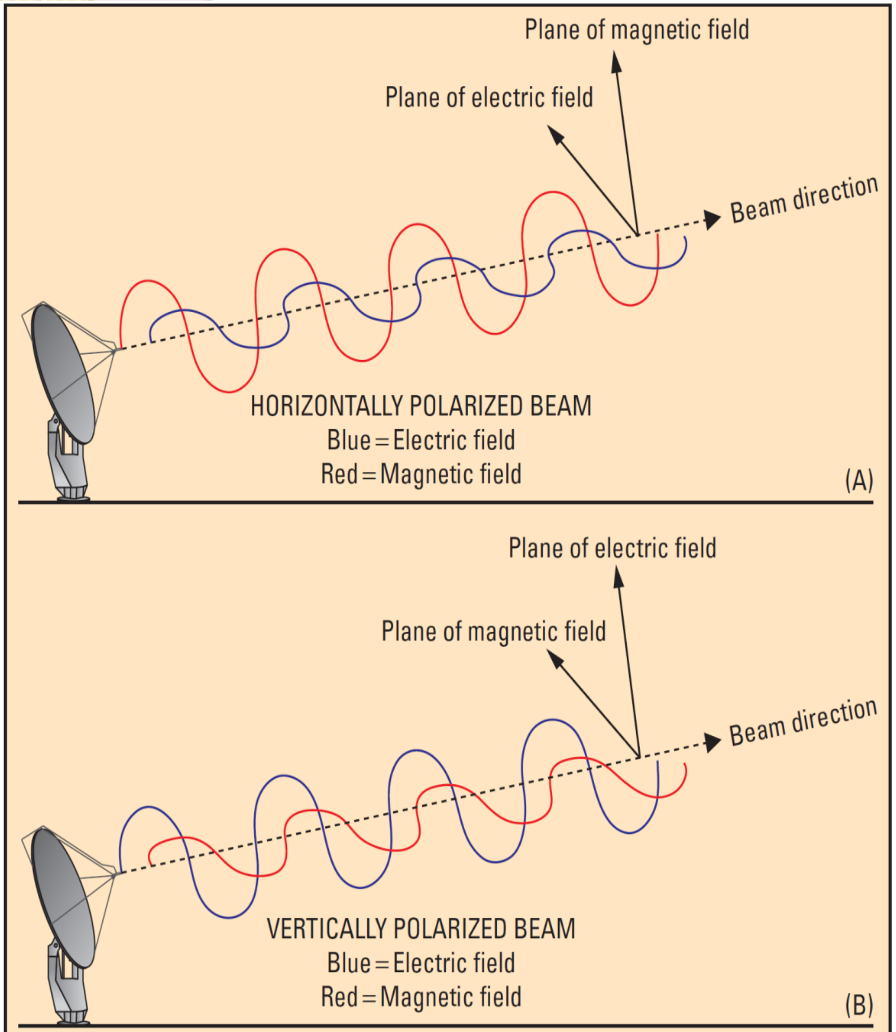
Dual-Pol radar can discriminate different particle shapes & precipitation types

Differential reflectivity: a measure of the shape of the particles within the beam.

Panel (c): **hail has high dBZ and low differential dBZ values.** Most hail is above 4 km (freezing level). But the downward pointing finger of hail is most likely to reach the ground.

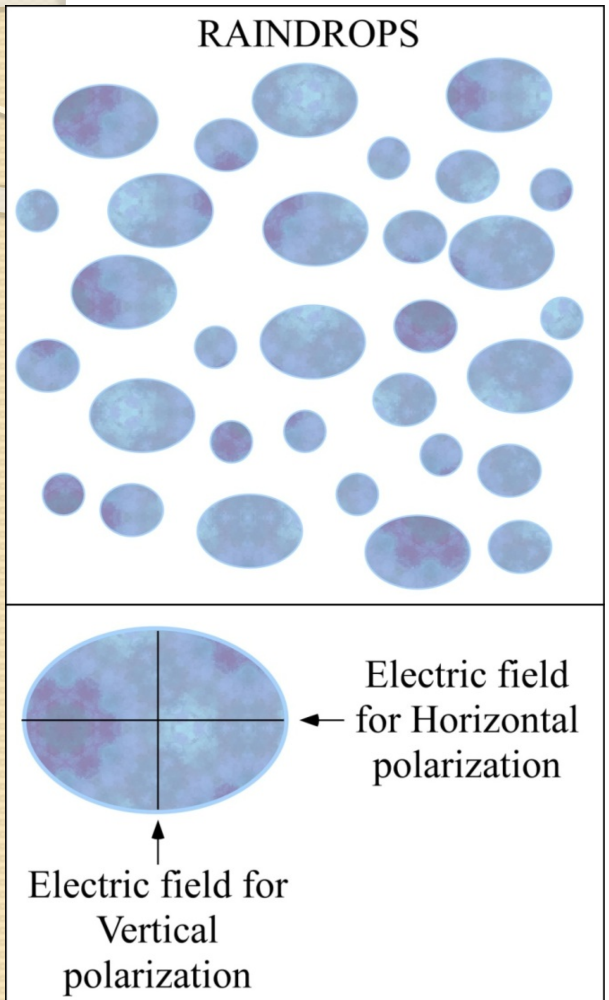


Radar Polarization



- **Radar transmit EM waves** with oscillating electronic and magnetic fields. **E and M fields are perpendicular** to each other and to the direction of radar beam.
- **Convectional radar**: E field oscillates in a plane horizontally (parallel to Earth surface)—Horizontally Polarized (A). Some radars could be Vertically Polarized (B).
- **Dual-Pol Radar**: The orientation of the electric field (polarization) is switched back & forth between horizontal & vertical orientation.
- **Differential reflectivity** is the ratio of the reflectivity measured at horizontal polarization to that at vertical polarization.

Differential Reflectivity of Rain & Hail



- **Raindrops:** oval shape. Horizontally polarized reflectivity is larger than vertically polarized reflectivity. Therefore, differential reflectivity is 1-2 dB for moderate rain & 3-4 dB for heavy rain.
- **Hailstones:** some are spherical, others have different shapes. But overall, hailstones fall randomly with no preferred orientation. Therefore, when radar views a large number of hailstones, the differential reflectivity is about 0 dB.