Chapter 3

CONVECTIVE WEATHER

I. THUNDERSTORMS. There are three basic storm types: single cells, multi-cells and supercells. This section will cover each storm type, unique characteristics of each, and associated severe weather. Thunderstorm-produced severe weather may consist of a combination of tornadoes, hail, strong winds, lightning, and heavy rainfall.

While upward vertical motions and instability of an air mass determine whether thunderstorms will occur, wind shear strongly influences the type of thunderstorms to expect. Other conditions being the same (and favorable to thunderstorm formation), the greater the shear, the more likely the convection will be sustained. Each type of storm can be identified by a distinctive hodograph pattern, a visual depiction of the wind shear. AWS/FM-92/002 describes hodograph construction and use. The SHARP computer program will produce hodographs from RAOB soundings. Both are available from the AFWTL. Knowing expected storm type is key to predicting severe weather.

A. THUNDERSTORM TYPES

1. Single Cell. Single-cell storms are short-lived (30 to 60 minutes) with one updraft that rises rapidly through the troposphere. Precipitation begins at the mature stage as a single downdraft. When the downdraft reaches the surface, it cuts off the updraft and the storm dissipates. Figure 3-1 is a typical diagram of a hodograph for a single-cell storm.

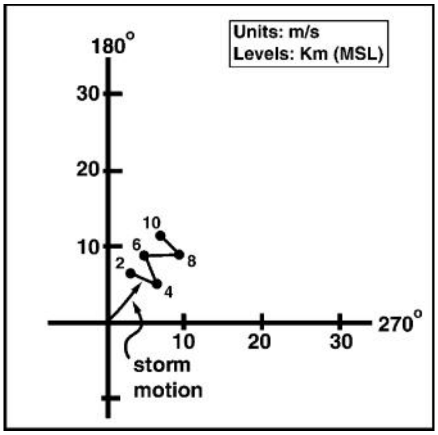

Figure 3-1. Single-Cell Storm Hodograph.

a. Single-cell Storm Indicators.

- Weak vertical and horizontal wind shear.
- The shear profile on the hodograph has a random pattern.
- Storm motion is with the mean wind in the lowest 5 to 7 km.

b. Associated Severe Weather.

- Tornadoes are rare.
- Short-lived high winds and hail are possible.

Watch developing cells using weather radar. When severe weather occurs in single-cell storms, it usually is in the stronger and longer-duration cells. Individual cells develop stronger core reflectivity at higher elevations than surrounding cells and must be closely monitored.

2. Multicellular. Multicellular storms are clusters of short-lived single-cell storms. Each cell generates a cold outflow that can combine to form a gust front. Convergence along this boundary causes new cells to develop every 5 to 15 minutes in the convergent zone. These storms are longer in duration than single-cell storms because they typically regenerate along the gust front. Figure 3-2 is a typical hodograph for a multicellular storm.

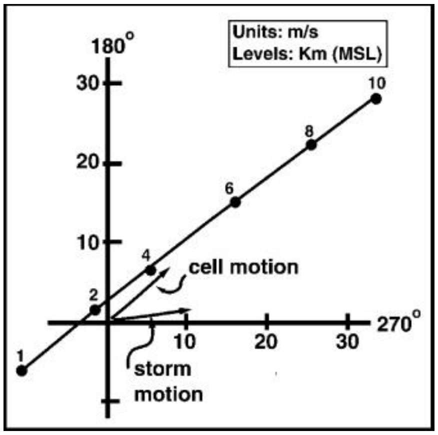

Figure 3-2. Typical Multicell Storm Hodograph.

a. Multicellular Storm Indicators.

- A straight-line or unidirectional shear profile.

- Strong directional shear in the lower levels, and strong speed shear aloft.

- Cell motion coincides with mean wind.

- Storm clusters propagate in the direction of the gust front and to the right of the mean wind.

b. Associated Severe Weather.

- Flash flooding from slow-moving cells.

- Large hail near downdraft centers.

- Short-duration tornadoes possible along gust fronts near updraft centers.

3. Supercell. Supercell thunderstorms consist of one quasi-steady rotating updraft, a forward-flanking downdraft that forms the gust front, and a rear-flanking downdraft. These storms exist for several hours and are a frequent producer of severe weather. There are three types of supercells: classic, high precipitation (HP), and low precipitation (LP). The hodograph for a supercell is pictured in Figure 3-3. The following indicate supercell storms:

- Wind speed increases with height.

- Shear vector veers with height in the lower levels, which can produce storm updraft rotation.

- Curved shear profile in lower levels becoming straight-line above 3 km.

- At least 70 degrees of directional shear in the first 3 km. Average amount of shear for a supercells is 90 degrees.

- A "cyclonically curved" hodograph, as shown in Figure 3-3, is associated with cyclonically rotating cells that move to the right of the mean (surface - 6 km) wind. "Anticyclonically curved" hodographs indicated storms moving to the left of the mean wind; These storms are notorious hail producers.

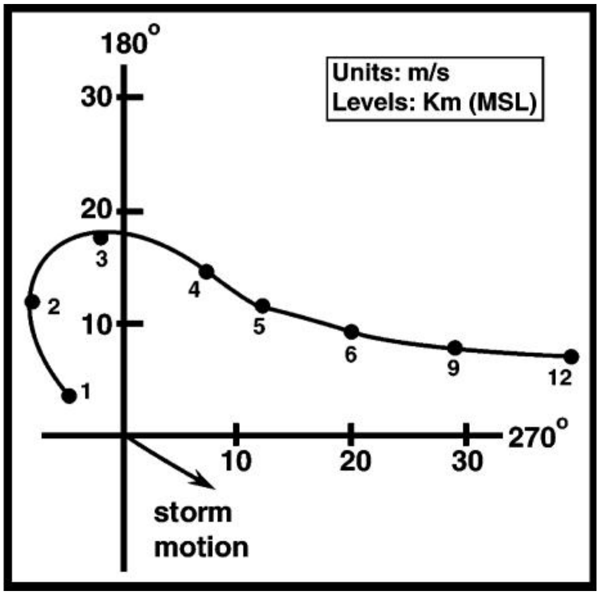

Figure 3-3. Supercell Hodograph. The figure shows a cyclonically curved hodograph.

a. Classic Supercells (Figure 3-4). Classic supercells are usually isolated per thunderstorm outbreak and are identified by the classic "hook echo" in the low-level reflectivity pattern and

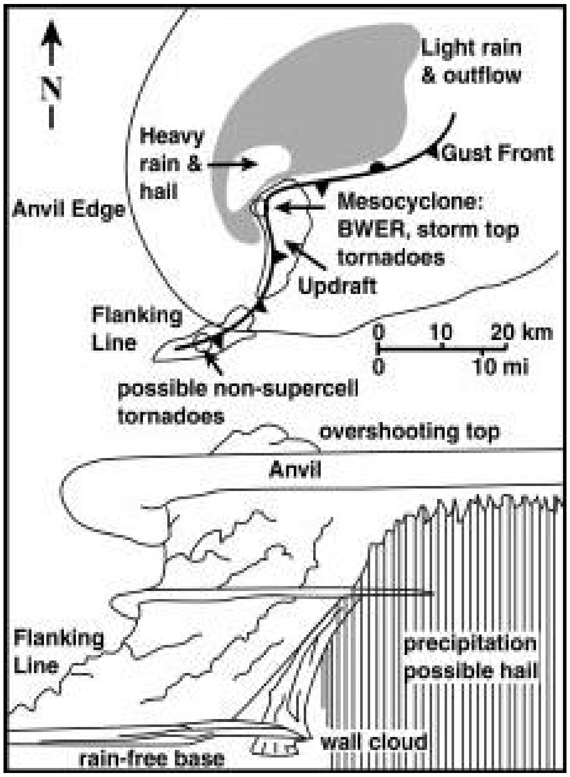

Figure 3-4. Classic Supercell. These supercells are indentified by a "hook echo" in the low-level reflectivity pattern.

bounded weak-echo region (BWER) aloft. These cells have the following associated severe weather:

- Golf ball-size hail.
- Possible tornadoes.
- Wind gusts in excess of 50 knots (along the gust front and from microbursts in the rear-flanking downdraft).

b. High Precipitation (HP) Supercells (Figure 3-5). These develop in deep moist layers with high moisture values. They are more common the further east you go from the Plains. They produce heavier rain than classic supercells and are not as isolated as these storms. Radar patterns associated with HP storms are more varied than the classical "hook". HP storms have the potential to evolve into bow echo configurations. Associated severe weather includes the following:

- Very heavy rain.
- Tornadoes and hail possible.

c. Low Precipitation (LP) Supercells (Figure 3-6). These storms are most commonly found along the dryline of west Texas. They produce some precipitation but have a rather "benign" appearance on radar. Although smaller in diameter then classic supercell storms, they are still capable of producing severe weather. These cells have the following associated severe weather:

- Large hail.
- Tornadoes.

4. Dry, Wet, and Hybrid Microbursts. Downbursts are dynamically enhanced concentrated downdrafts from thunderstorms that result in damaging winds with gusts of 50 knots or greater

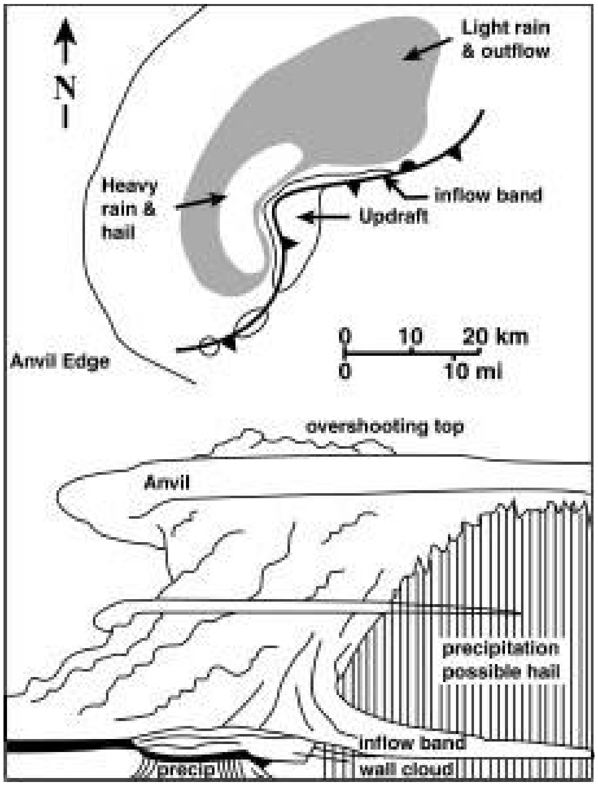

Figure 3-5. Typical High Precipitation (HP) Supercell. These supercells develop in deep, moist layers with high moisture values.

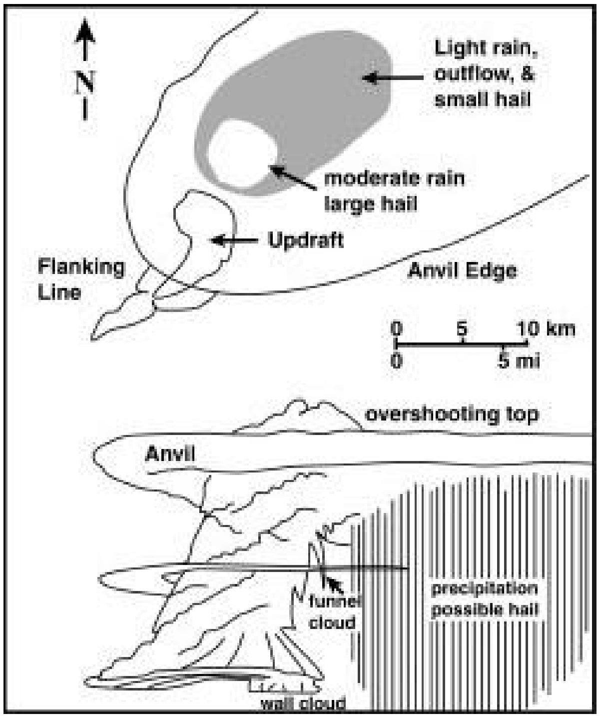

Figure 3-6. Low Precipitation (LP) Supercell. These storms occur most often along the dryline of west Texas.

at the surface. These usually occur in the rear-flanking downdraft region of supercell storms and may also be found behind the gust front. Downbursts/microbursts, however, are not restricted to large supercell storms; they can come from innocuous-looking, high-based rain clouds (dry microbursts) and from single- and multicellular pulse storms (wet microbursts), or from hybrid microbursts that combine dry and wet extremes. The microburst type depends on the type of environment where the formation of the storm takes place.

Figure 3-7a-c portrays typical atmospheric profiles for dry, wet, and hybrid microbursts. Currently, there is no method for predicting precisely when and where a microburst will occur, but if the environment is conducive to microburst occurrence, then the possibility for a microburst event can be incorporated into the forecast.

5. ***Derechos***. Derechos are straight line winds from severe convective storms. There are two types of derechos. The first are rapidly propagating segments of an extensive squall line associated with a strong, migratory low-pressure system that occurs late winter and spring. The second type develops in association with a relatively weak frontal system in a moisture-rich environment, showing characteristics of both squall lines and nonlinear types of MCSs, and is a late spring and summer event. They predominately occur along an axis from southern Minnesota through the Ohio River Valley but are not limited to that region.

II. SYNOPTIC PATTERNS. This section describes five basic severe thunderstorm-producing synoptic weather patterns for mid-latitudes and describes three well-acknowledged parameters used to identify areas for thunderstorm development: mid-level jets or shears; dry-air intrusions between 850 mb and 700 mb; and low-level moisture gradients. These parameters have proven to be useful to identify severe thunderstorm triggering mechanisms, and forecasting when and where severe thunderstorm outbreaks will occur in each of the synoptic patterns. Stability index usage for thunderstorm forecasting is covered later.

Mid-level jets can be used to determine areas of thunderstorm and tornado development. Mid-level

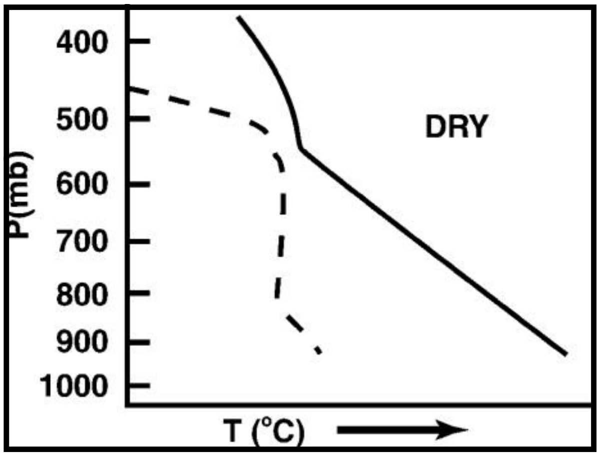

Figure 3-7a. Dry Microburst Atmospheric Profile. Typical atmospheric profile for dry microbursts.

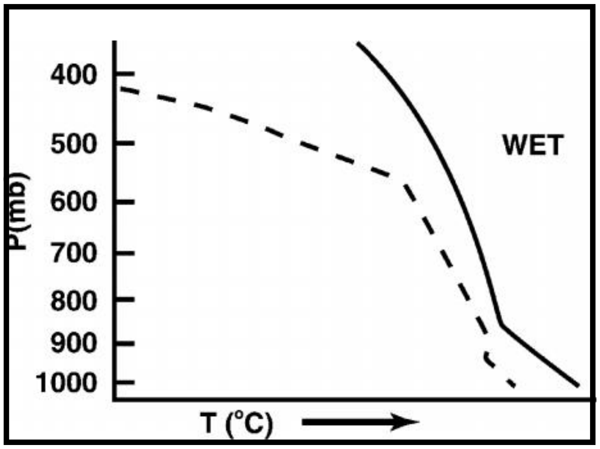

Figure 3-7b. Wet Microburst Atmospheric Profile. Typical atmospheric profile for wet microbursts.

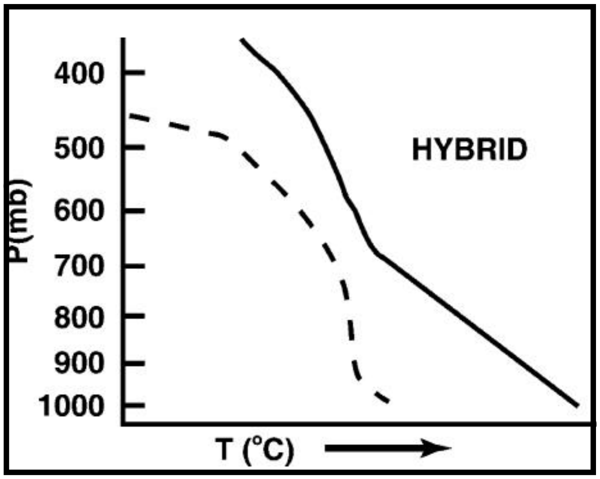

Figure 3-7c. Hybrid Microburst Atmospheric Profile. Typical atmospheric profiles for hybrid microbursts.

Table 3-1. Severe thunderstorm development potential.

Parameters	Weak	Moderate	Strong
Jet Speed	35 kt	35-50 kt	>50 kt
Horizontal Shear	15 kt/90 NM	15-30 kt/90 NM	>30 kt/90 NM
Winds crossing the axis of 700-mb dry intrusions and moisture boundaries	Less than 20° or not at all	20-40°	Greater than 40°
Surface Dew Point	< 13°C	13-18°C	> 18°C
850-mb Dew Point	< 8°C	8-12°C	> 12°C

jets are wind speed and shear maxima that occur between 10,000 and 20,000 feet, or roughly 700 mb to 500 mb. These jets should not be confused with upper-level polar front and subtropical jet streams. Table 3-1 shows an empirical relationship between threshold values for mid-level jet speeds and shear parameters and potential for severe thunderstorm development.

Dry-air intrusions between 850 mb and 700 mb are a major triggering mechanism for tornadoes and can be used to pinpoint areas of potential severe thunderstorm development. Dry-air intrusions are difficult to identify by a particular temperature/dew point spread or relative humidity since the values vary from case to case. They can often be identified by looking at the intensity with which the drier air is being forced into the moist air. Table 3-1 also shows an empirical relationship between the angle of the 700-mb winds and the dry-air intrusion axis, and severe thunderstorm potential.

Almost all severe thunderstorm outbreaks are associated with strong low-level (below 700 mb) moisture gradients except in the case of winds greater than or equal to 50 knots associated with dry microbursts. The moisture axes are generally located on the windward side of the outbreak area. The intensity of the storm is usually proportional to the tightness of the moisture gradient along the wind component from dry to moist air.

Note: When the 850-mb or 925-mb product is not representative of moisture below 700 mb, the moisture gradient can often be determined from satellite imagery and computer-generated vertical cross sections.

A. FIVE CLASSIC SYNOPTIC CONVECTIVE WEATHER PATTERNS. Five classic synoptic severe weather patterns are generally associated with the development of severe mid-latitude thunderstorms. The characteristics of the thunderstorm outbreak area(s), triggering mechanism(s), and timing rule(s) are identified for each of the patterns. Pattern recognition provides clues to which type of weather severity is possible in each situation.

Keep in mind these weather patterns are idealized, and various elements used to define the synoptic patterns may be located or oriented differently in other areas of interest. In some instances, more than one pattern may apply to one area. Look for a “best fit” of the weather patterns to the area of interest.

Note: Air-mass (pulse) thunderstorms, (thunderstorms not associated with any recognizable frontal systems) are covered later in this chapter.

1. Type A Thunderstorm Pattern, "Dryline." (Figure 3-8).

a. Pattern Characteristics.

- Well-defined southwesterly 500-mb jet.

- Distinct, warm dry-air intrusion from the southwest, surface to 700 mb.

- Considerable streamline confluence (850 mb to 700 mb) along the dry line.

- Low-level moisture (surface to 850 mb) advection from the south, ahead of dry air.

- Convective development characterized by unusually rapid growth (15 to 30 minutes) from inception to maturity with almost immediate production of very large hail, damaging winds, and tornadoes (usually in groups or families).

b. Initial Outbreak Area.

- Storms are usually confined to the edges of the dry air at 850 mb and 700 mb.

- The convergence zone between the moist and dry air (area of maximum gradient from dry to moist air).

- These storms form rapidly, in isolated clusters, along the leading edge of the dry intrusion. (Sharp, well-defined squall lines are not common with this pattern.)

c. Severe Weather Area.

- Severe thunderstorms often extend along and to about 200 miles to the right of the 500-mb jet (in the diffluent zone), and from the maximum low-level convergence, downstream to the point where the low-level moisture decreases to a value

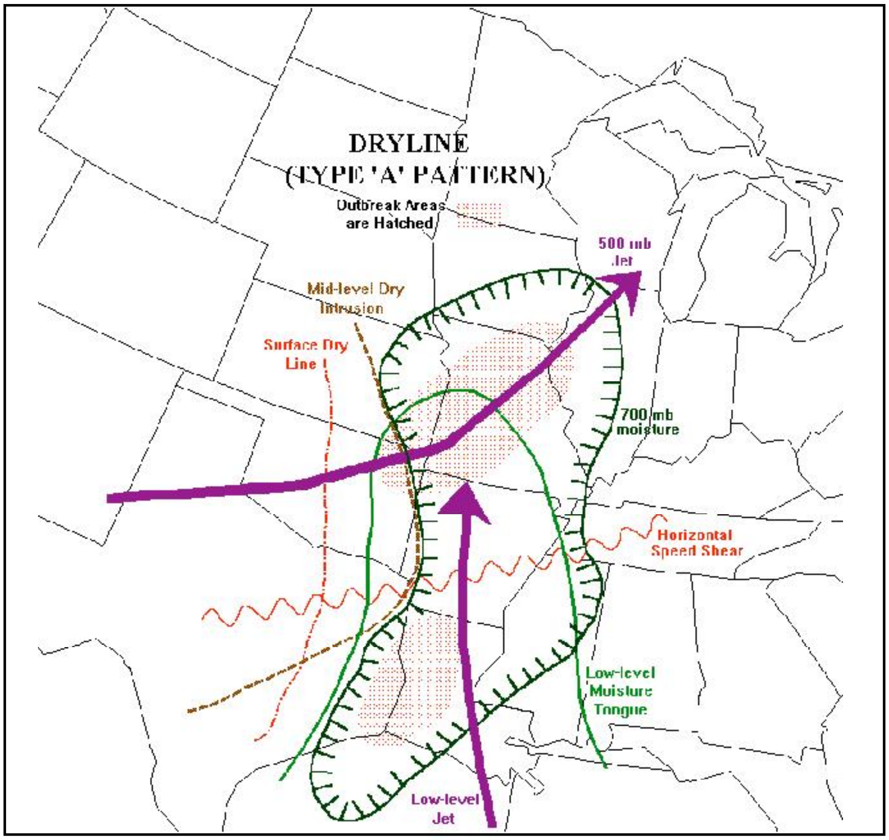

Figure 3-8. Type "A" Thunderstorm Pattern. The most violent storms usually form where the jet meets the moist and dry-air convergence zone.

insufficient to support severe weather. The most violent storms usually form where the jet meets the moist and dry-air convergence zone.

- A secondary severe weather outbreak area may be located along and 150 miles to the right of the 500-mb horizontal speed shear zone, and from the maximum low-level convergence, downstream until a decrease in sufficient moisture to produce severe weather.

d. Triggering Mechanisms.

- Maximum diurnal heating.
- Passage of the upper-level jet maximum.
- A low-level intrusion of warm, moist air.
- Dry air moving into a low-level moist region.

e. Timing.

- Thunderstorms begin about the time of maximum heating.
- Convection is usually suppressed by an inversion until the convective temperature is reached.
- The activity usually lasts 6 to 8 hours, or until the mixing of moist and dry air masses is complete and low-level winds diminish.

2. Type B Thunderstorm Pattern, "Frontal" (Figure 3-9). The convective development pattern is characterized by prefrontal squall lines with one or more mesoscale lows (25 to 100 miles in diameter) that form at the intersection of the low-level jet (850 mb) and the 500-mb jet. Mesoscale lows may form in the area of the intersection of the

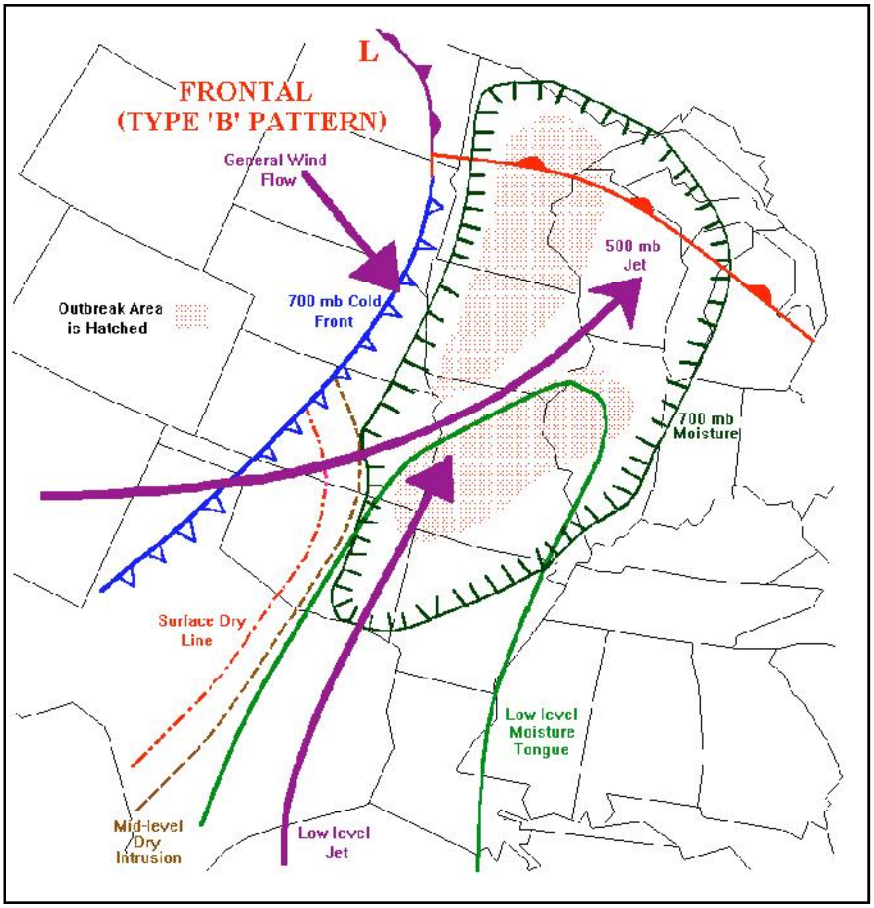

Figure 3-9. Type "B" Thunderstorm Pattern. Tornado families are usually associated with any mesoscale lows that form.

low-level jet and the warm front. Tornado families are usually associated with any mesoscale lows that form.

a. Pattern Characteristics.

- Well-defined southwesterly jet at 500 mb.

- Well-defined dry intrusion (surface to 700 mb).

- Strong low-pressure center, cold and warm fronts.

- Frontal and prefrontal squall lines almost always form.

- Strong cold-air advection behind the cold front (surface to 500 mb).

- Warm low-level (surface to 850 mb) jet transporting moisture from the south.

- Cool, moist air at the 700-mb and 500-mb cold trough axes, which lie to the immediate west of the threat area.

- Considerable low- and mid-level streamline confluence at altitudes between the low-level warm, moist air and the cooler air aloft.

b. Initial Outbreak Area.

- Mesolows may form at the intersection of the low-level jet and the warm front.

- Location depends on the speed of the cold front and the dry surge into the moist air.

- The severe weather area extends along and 200 miles to the right of the 500-mb jet (in the diffluent zone) and from the dry intrusion to where the low-level moisture becomes insufficient to support severe weather activity.

- Initial outbreak usually occurs along or just ahead of the surface cold front in the region where strong upper-level cold-air advection, strong low-level warm moist advection, and southwesterly dry intrusion all occur. The outbreak area occurs in the area of maximum cold-air advection (500 mb) and dry-air advection at 850 mb and 700 mb.

c. Secondary Outbreak Area.

- Squall lines often form about 150 to 200 miles north of the jet, extending south to the leading edge of the dry-air intrusion.

- Located along and 150 miles to the right of the horizontal speed shear zone and from the dry intrusion to where the low-level moisture becomes insufficient to support further activity.

d. Triggering Mechanisms.

- Movement of the dry line.

- Intersection of low-level jet (850 mb) with the warm front.

- Intersection of the low-level jet (850 mb) with the 500-mb jet.

- Intersecting lines of discontinuity (i.e., squall lines, jet streams, and/or fronts).

e. Timing.

- Anytime; may last all day and night (doesn't depend on diurnal heating).

- Will last as long as the air mass ahead of the squall remains absolutely unstable.

Note: On rare occasions, the severe activity may last longer if the dry line is driven by a 30-knot or greater wind from the surface through 700 mb.

3. Type C Thunderstorm Pattern, "Overrunning" (Figure 3-10). The area of overrunning-produced thunderstorms is enhanced by dry intrusions. The outbreak area is favorable for the development of mesoscale lows and mesoscale highs. These mesoscale features move in a direction 30 degrees to the right of the 500-mb flow toward higher temperatures and lower pressures. There are intense pressure gradients around these mesoscale features. Tornadoes occur either singly or by two's and three's separated by

25 to 50 miles. This pattern changes to a Squall Pattern if a well-defined cold front accompanied by strong cold-air advection overtakes the active thunderstorm area.

a. Pattern Characteristics.

- East-west stationary frontal zone with warm, moist tropical overrunning air.

- West-southwest to west-northwest positioned 500-mb jet, or a strong 500-mb westerly horizontal wind speed shear zone.

- Dry intrusion from the southwest present at 700 mb. (if a dry intrusion doesn't exist, severe thunderstorms are not likely.)

- Tornadoes may occur with surface dew points of 50°F (14°C) or higher. Release of latent heat is usually considered fuel for combustion. Widespread large hail and damaging winds may also be present.

b. Initial Outbreak Area.

- Scattered thunderstorms develop on and to the north of the front as a result of overrunning.

- Thunderstorm activity reaches severe limits as the squall line forms along the leading edge of the dry intrusion.

- Hail producer if the Wet-bulb zero height is favorable for severe weather.

- Severe weather threat area occurs between the 500-mb jet and the stationary front. The western edge of activity extends for 50 miles west of the axis of maximum overrunning, and the eastern edge depends on a decrease in temperature lapse rate and/or a decrease in overrunning.

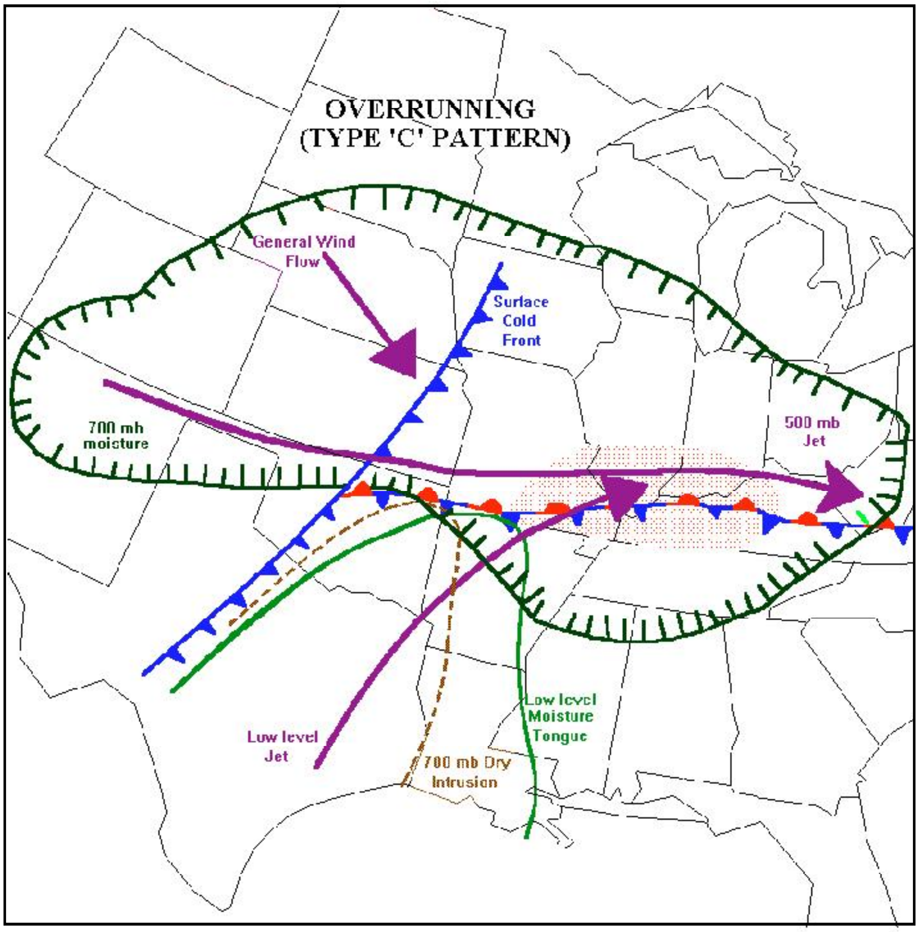

Figure 3-10. Type "C" Thunderstorm Pattern. Tornadoes occur either singly or by two's and three's separated by 25 to 50 miles.

- Usually no area of secondary outbreaks.

c. Triggering Mechanisms.

- Overrunning.

- Maximum diurnal heating.

- Severe storms triggered by a dry intrusion moving into an area of active storms.

d. Timing.

- When the dry intrusion is lost, storm intensity falls below severe criteria.

- Maximum activity occurs for 6 hours after maximum heating or when a dry intrusion enters the area.

4. Type D Thunderstorm Pattern , "Cold Core" (Figure 3-11). Widespread storms produce hail and numerous funnel clouds; tornadoes occur singly, not in families, and they seldom occur.

a. Pattern Characteristics.

- Deep southerly 500 mb jet.

- Surface low deepening.

- 500-mb cold-core low.

- Cool, dry-air advection at all levels around the bottom of the low.

- Low-level jet advecting warm, moist air from south-southeast toward the north and under the cold air aloft.

b. Initial Outbreak Area.

- Hail of increasing frequency and size westward from the jet to the 500-mb cold-core low.

- In the warm, moist under-running air between the 500-mb jet and the cold closed isotherm center at 500 mb.

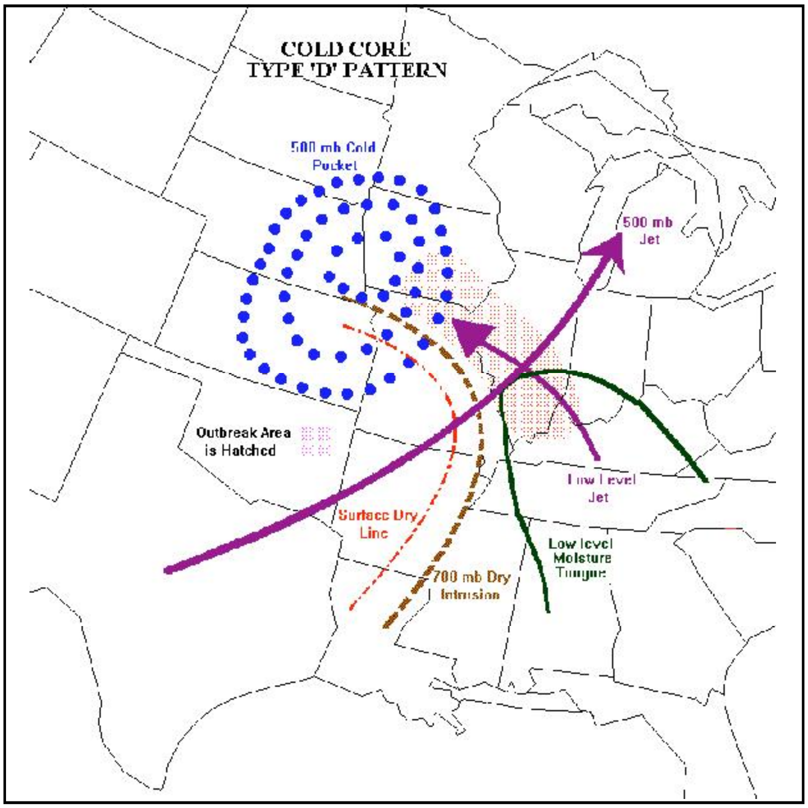

Figure 3-11. Type D Thunderstorm Pattern , "Cold Core." Widespread storms produce hail and numerous funnel clouds, but tornadoes seldom occur.

- Severe weather extends from approximately 150 miles to the right of the 500-mb jet to the cold core low center and from the intense low-level confluence ahead of the dry intrusion (southwest boundary) to the east and northeast limit of the under-running unstable warm, moist air.

c. Triggering Mechanisms.

- Intense low-level wind confluence.

- Increasing instability caused by the 500-mb cold-air advection over the low-level warm moist advection.

d. Timing.

- Weaker storms can occur at any hour.

- Intensity of storms decreases rapidly after sunset.

- The most violent storms occur between noon and sunset, during maximum diurnal heating.

5. Type E Thunderstorm Pattern, "Squall Line" (Figure 3-12). Frontal or prefrontal squall lines are almost always well defined.

a. Pattern Characteristics.

- Well-defined westerly jet at 500 mb.

- Well-defined dry source bounded by a 700-mb warm sector.

- Considerable low-level convergence and a squall line forms in virtually all cases.

- Moderate to strong south to southwest low-level flow advecting warm moist air over cooler air (usually ahead of a warm front).

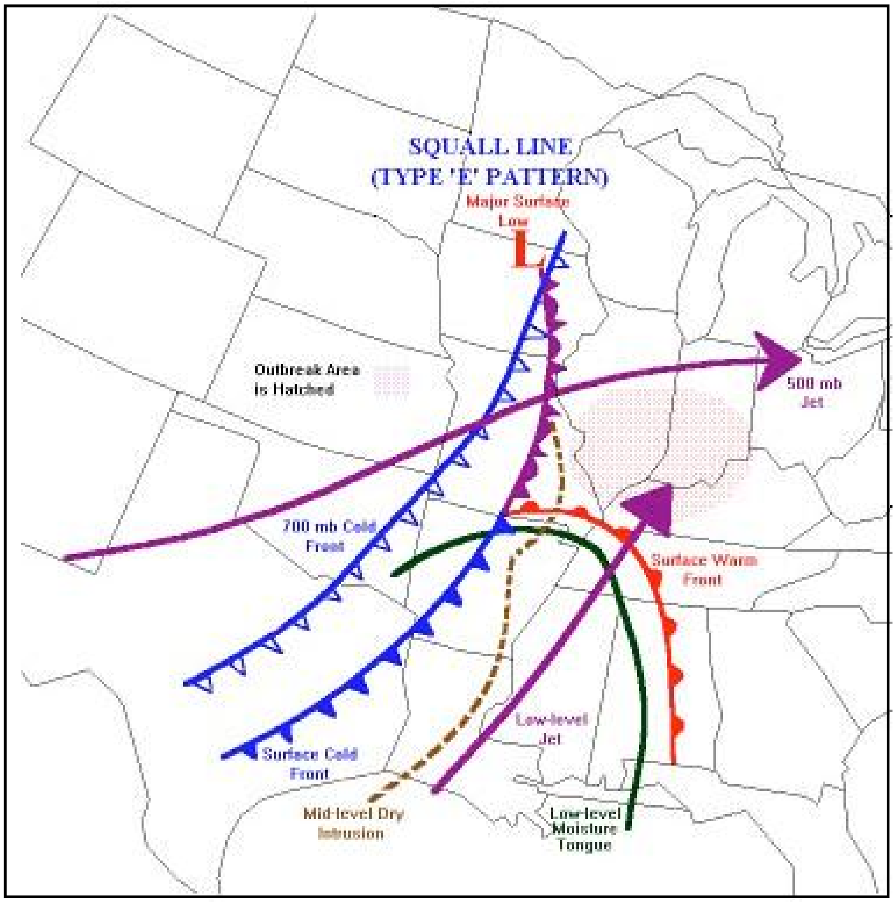

Figure 3-12. Type E Thunderstorm Pattern, "Squall Line." Maximum severe activity, both quantity and intensity, occur from maximum heating to a few hours after sunset.

b. Initial Outbreak Areas.

- Severe weather usually extends along and south of the 500-mb jet but north of the 850-mb warm front and from the 700-mb cold front to the place where instability decreases to a value insufficient to support severe activity.

- Thunderstorms form in the overrunning moist air between the 850-mb warm front and the upper-level jet axis where the 700-mb dry-air intrusion meets the frontal lifting of the warm, moist low-level air and the strong 500-mb cold-air advection.

c. Secondary Outbreak Areas.

- If the 700-mb dry intrusion extends to the south of the 850-mb warm front, outbreaks can occur along the 500-mb horizontal speed shear zone and along transitory, but active, squall lines.

d. Triggering Mechanisms.

- Diurnal heating.

- 700-mb dry intrusion moves into threat area.

- Frontal lifting of warm moist air triggers the initial outbreak.

- Cold-air advection at 500 mb into threat area increases severity of storms.

e. Timing.

- Onset of 500-mb cold-air advection into threat area.

- Maximum severe activity, both quantity and intensity, occur from maximum heating to a few hours after sunset.

- Many severe thunderstorms continue until midnight, or until the air mass becomes too stable to produce severe activity.

III. CONVECTIVE WEATHER TOOLS. The thermal stability or instability of a column of air can be conveniently expressed as a single numerical value called a stability index. These indices are aids for forecasting thunderstorms and should not be used as the sole basis for making a thunderstorm forecast. Detailed procedures for calculating many of these indices can be found in AWS/TR—79/006. See also various PC programs such as SHARP or Skew-T Pro, available from the AFWTL.

A. STABILITY INDICES

1. Convective Available Potential Energy (CAPE). This is a measure of the convective instability of the atmosphere and, thus, thunderstorm potential. It is calculated using the most unstable parcel in the lowest third of the atmospheric model. CAPE values are not a direct indicator of severe weather. They should be used in conjunction with helicity (a measure of the rotation potential of a column of air) for forecasting severe weather. Use values above 200 J/kg in conjunction with helicity to determine conditions for tornadic thunderstorms and severe weather. Be aware that violent thunderstorms and tornadoes are associated with a wide range of values.

2. Bulk Richardson Number (BRN). The BRN is a better indicator of storm type than of storm severity or storm rotation. It is useful in differentiating between weak, multicellular storms (non-severe) and super-cell-storm (severe) types. The BRN is a measure of turbulent energy (a ratio of buoyancy to vertical wind shear) in a column of air to enhance or hinder convective activity

- Works best when CAPE index is 1,500 to 3,500 J/kg.

- When CAPE is less than 1,000 J/kg and accompanied by moderate wind shear, the BRN value may indicate supercells, but the lack of buoyancy is likely to inhibit severe weather occurrence.

- When CAPE is greater than 3,500 m^2/s^2 with a moderate wind shear environment, BRN values may suggest multicellular storms (non-severe storms), but the buoyant energy will be sufficient to produce tornadoes and large hail.

Note: Using BRN might not be as useful for predicting tornado development as it is for predicting multi- vs super-cell type thunderstorm.

Strong tornadoes have developed in environments with BRN values ranging from 0 to 40.

3. Cross Totals (CT). Cross Totals is most effective for thunderstorm coverage and severity east of the Rockies and along the Gulf Coast. It measures a combination of low-level moisture and upper-level temperature. The CT value is contingent on the low level moisture band being at 850 mb and a cold air pocket at the 500 mb level. If the moisture and cold air are centered slightly above or below these levels, CT values will not be a reliable indicator of thunderstorm coverage or severity.

4. Dynamic Index. This index is designed for air-mass thunderstorms. Positive values indicate stability, and negative numbers indicate a conditionally unstable air mass. A triggering mechanism is needed for thunderstorms to occur when conditionally unstable, diurnal heating is usually enough to trigger the convection.

5. Energy/Helicity Index (EHI). Use this index only if strong thunderstorms are forecast. As mentioned previously, CAPE cannot be used alone to forecast severe weather. EHI is a combination of CAPE and Storm-Relative Helicity (S-RH), which measures the contribution of convective instability of the atmosphere and the shear vorticity to the potential for tornado formation. Strong to violent tornadoes are associated with a wide range of CAPE values: large CAPE values combined with low wind shear, and conversely, low CAPE values combined with high wind shear are both capable of producing conditions favorable for the development of tornadoes (mesocyclogenesis).

6. Fawbush-Miller Stability Index (FMI). This index is similar to the Showalter Stability Index, except it emphasizes the low-level (surface) moisture rather than the 850-mb moisture. The FMI can be more representative than the Showalter Index, however, computation of the FMI is definitely more difficult (Ref: AWS/TR-79/006). Use only when the Showalter appears to be misrepresenting the low level moisture.

7. GSI Index. This index was developed for use in the central Mediterranean using the following procedure:

Step 1. Obtain the minimum temperature/dew point spread (°C) between 650 mb and 750 mb

Step 2. Obtain the average wet-bulb temperature in the lowest 100 mb by the equal area method. From this point, follow the saturation adiabat to the 500-mb level. Subtract the temperature were the saturation adiabat crosses 500 mb from the observed 500-mb temperature (°C).

Step 3. Add the values from Step 1 and Step 2 above to calculate GSI.

Example: If the saturation adiabat crosses the 500-mb level at -20°C, and the observed 500-mb temperature is -15°C, then the value would be -5.

8. K Index (KI). The K Index is primarily used to forecast heavy rain and thunderstorm potential. It is not a good indicator of severe vs non-severe weather. The K index was developed for pulse (air-mass) thunderstorm forecasting. It works best in the summer east of the Rockies in maritime-tropical (mT) air masses and in any tropical region. It has limited use in overrunning situations and in mountainous regions.

Note: KI Values over 35 represent heavy rain potential and a flood threat, especially when a series of storms travel over the same area.

9. KO Index (KO). The KO index, created by the German Weather Bureau, is sensitive to moisture and works best for cool moist climates (mP), (i.e., Europe, Pacific Northwest). The KO Index's drawback is its complexity. Unlike most other indices, the standard Skew-T programs do not calculate it. The KO equation is:

$$\mathrm{KO} = \frac{\left(\theta_{e_{500}} + \theta_{e_{700}}\right)}{2} - \frac{\left(\theta_{e_{850}} + \theta_{e_{1000}}\right)}{2}$$

(Where θ_e is the equivalent potential temperature at a given level.)

To find θ_e, first find the lifting condensation level (LCL) for the given pressure level. Continue up the moist adiabat until all moisture is removed from the parcel. This occurs at the level where the moist and dry adiabats become parallel. From there, continue up the dry adiabat to the top edge of the chart. There, read θ_e directly. Do this for each of the four pressure levels in the equation and plug into the equation. The result is the KO index. (Ref: AWS/FM-90/001)

10. Lifted Index (LI). The LI can be used successfully at most locations since it contains a good representation of the low-level moisture. This index counters deficiencies in the Showalter Index when low-level moisture and/or inversions are present. The LI fails to consider destabilizing effects of cold air above 500 mb. Threshold values generally are lower than Showalter Index.

11. Mean Storm Inflow (MSI). Use the SHARP computer program to derive the MSI index. It measures the potential strength of inflow to a storm, which contributes to the development of storm rotation. Mesocyclones, known tornado producers, require storm rotation in order to develop.

12. Modified Lifted Index (MLI). The MLI considers the destabilizing effects of cold air aloft, which the LI fails to take into account. It works well as a severe thunderstorm indicator in Europe, though it has been used with success in the CONUS. It gives poor results when the -20°C level is above 500 mb (too warm) or below the LCL (too cold).

13. S Index (S). The German Military Geophysical Office (GMGO) developed this index from the Total Totals (TT) index. The S Index adds the 700-mb moisture and a variable parameter based on the Vertical Totals (VT). The addition of 700-mb moisture tailors this index for sections of Europe since low-level heating is usually less intense in parts of Europe than in the States, and 700-mb moisture is a good predictor of thunderstorm development there. The S-Index is useful from April to September. It can be computed from the equation:

$$S = TT - (700T - 700T_d) - A$$

Where A is defined as follows:

- If $VT > 25$ then $A = 0$
- If $VT \geq 22$ and ≤ 25 then $A = 2$
- If $VT < 22$ then $A = 6$

14. Severe WEAther Threat Index (SWEAT). The SWEAT index is designed to predict severe storms and tornadoes, rather than ordinary thunderstorms. High SWEAT values do not necessarily mean that severe weather will occur since it doesn't consider triggering mechanisms. High SWEAT values based on the morning sounding do not necessarily imply severe weather will occur. If SWEAT values remain high for the forecast sounding, then severe weather potential is high.

15. Showalter Stability Index (SSI). This index works best in the Central US with well-developed systems. This index is a first indication of instability. It doesn't work well if a frontal surface or inversion is present between 850 mb and 500 mb. It also is not a good predictor of severe weather when low-level moisture is present below 850 mb. See Fawbush-Miller or Lifted Index.

16. Storm Relative Directional Shear (SRDS). SRDS is also a SHARP-derived index, used to measure the amount of directional shear in the lower 3 km of the atmosphere, and strong directional shear significantly contributes to storm rotation.

17. Storm-Relative Helicity (S-RH). Helicity has been found to correlate strongly with the development of rotating updrafts. The correlation with tornadoes is less clear. Helicity is very sensitive to the storm motion. Storms that encounter boundaries or slow down can have radically different helicities than the general environment. A high-helicity, low-shear environment is possible.

18. Surface Cross Totals (SCT). Use SCT to predict severe potential for areas at high elevations.

19. Thompson Index (TI). Use TI to determine thunderstorm severity over or near the Rockies.

20. Total Totals (TT). Use TT to forecast thunderstorm coverage and severity. This index is particularly good with cold air aloft. It may over-forecast severe weather when sufficient low-level moisture is not available. The TT index is the sum of the Vertical Totals and Cross Totals.

21. Vertical Totals (VT). Use VT in the western U.S., UK, and western Europe to predict thunderstorm potential.

*22. **Wet-Bulb Zero Height (WBZ).*** The WBZ is often a good indicator of hail and surface gusts 50 knots or greater when it lies between 5,000 to 12,000 feet, and of tornadoes, when it lies between 7,000 to 9,000 feet. It is not a good indicator for mT air masses, which naturally have high WBZs; hail or strong surface gusts rarely occur in these air masses outside the immediate vicinity of tornadoes. Many studies indicate a strong correlation between the height of wet-bulb zero and the types of tornadoes that will occur. While it doesn't directly forecast the occurrence of tornadoes, WBZ can help predict whether tornadoes will form in families or singularly once tornadoes are forecast.

Table 3-2 lists various general thunderstorm forecast indices and threshold values; Table 3-3 lists indices and threshold values for forecasting severe weather potential. Tables 3-4 and 3-7 list various tornado indicators. Thresholds vary somewhat from site to site, so closely monitor these values to discover the best value for local use and adjust accordingly. The best way to evaluate a threshold is to keep a continuous record of their effectiveness. Regional values are given where data are available. See also Tables 3-11 to 3-14 for regional summaries.

Table 3-2. General thunderstorm (instability) indicators.

Index	Region	Weak (Low)	Moderate	Strong (High)
CAPE		300 to 1000	1000 to 2500	2500 to 5300
Cross Totals (CT)	East of Rockies	< 18 No thunderstorms	18 to 19	≥ 20
	Gulf Coast	< 16 No thunderstorms	20 to 21	
Dynamic Index	For airmass thunderstorms	Positive numbers		Negative numbers
Fawbush-Miller Index (FMI)		0 to -2	–2 to -6	–6 and lower Severe possible
GSI Index	Mediterranean	> 8 Thunderstorms		≤ 8 Thunderstorms
K-Index (KI)	East of Rockies (mT air masses), and the Tropics	20 to 26	26 to 35	> 35
	West of Rockies (mT)	15 to 21	21 to 30	> 30
KO-Index (KO)	Cool, moist climates: Europe, Pacific NW	>6	2 to 6	<2
Lifted Index (LI)		0 to -2	-3 to –5	–5 and lower
S-Index	Europe, April-September only	< 39 No thunderstorms	> 40 and < 46 Thunderstorms possible	> 46 Thunderstorms likely
Showalter Stability Index (SSI)	US	≥ +3	+2 to –2	≤ –3 Severe possible
	Europe	> 2 No thunderstorms	≤ 2 Thunderstorms possible	
Total-Totals (TT)	West of Rockies	48 to 51	52 to 54	> 54
	East of Rockies	44 to 45	46 to 48	> 48
	Europe	> 42	> 48	> 50
Vertical Totals (VT)	US: general			≥ 26
	Gulf Coast			≥ 23
	West of Rockies	< 28 No thunderstorms	28 to 32	> 32
	UK			> 22
	W. Europe			> 28

Table 3-3. Severe thunderstorm indicators.

Index	Region	Weak (Low)	Moderate	Strong (High)
Bulk Richardson Number (BRN)		> 50 Multi-cellular storms		10 to 50 Supercells
Cross Totals (CT)	East of Rockies	22 to 23	24 to 25	> 25
	Gulf Coast	16 to 21	22 to 25	> 25
	West of Rockies	< 22	22 to 25	> 25
Modified Lifted Index	Europe	0 to -2	-3 to -5	-5 and lower
Surface Cross Totals (SCT)	East of 100°W			≥ 27
	High Plains			≥ 25
	Foothills of Rockies			≥ 22
SWEAT Index	Midwest and Plains (unreliable at higher elevations)	<275	275 - 300	≥ 300
Thompson Index (TI)	Over the Rockies	20 to 29	30 to 34	≥ 35
	East of Rockies	25 to 34	35 to 39	≥ 40
Total-Totals (TT)	West of Rockies	55 to 57	58 to 60	≥ 61
	East of Rockies	48 to 49	50 to 55	≥ 56
Wet-Bulb Zero Height	Not for use with mT air masses	< 5,000 ft	7,000 to 9,000 ft	Tornadoes
			5,000 to 12,000 ft	Large hail

Table 3-4. Tornado Indicators.

Index	Value	Interpretation
Energy/Helicity Index (EHI)	0.8 to 1 1 to 4 > 4	Weak tornadoes. Strong tornadoes. Violent tornadoes.
Lifted Index (LI)	< –6	Tornadoes possible.
Mean Storm Inflow (MSI)	> 20	Mesocyclone development possible.
Showalter Index (SSI)	≤ –6	Tornadoes possible.
Storm Relative Directional Shear (SRDS)	> 70	Mesocyclone development possible
Storm Relative Helicity (s-rH)	≥ 400	Tornadoes possible.
SWEAT Index	≥ 400	Tornadoes possible.
Wet-Bulb Zero Height	7,000 to 9,000 ft (mP)	Families of tornadoes.
	≥ 11,000 ft (mT)	Single tornadoes.

B. EVALUATION AND TECHNIQUES. There are many data sources and tools available to the forecaster: atmospheric models and numerical analysis techniques; satellite, radar, and conventional upper-air data; and a variety of software applications designed to help forecasters interpret these data. Some of these programs are available on the Internet. Deciding which tools and data to use in forecasting severe convective weather can be an overwhelming task. Using the following techniques and rules of thumb may help in organizing your thoughts as you move through the forecast process. Start by knowing the typical "seasons" for thunderstorm activity in the geographical area of interest as described in Regional Climatologies produced by AFCCC.

1. Synoptic Evaluation for Potential Severe Weather. Begin by determining if the current and/or forecast weather is favorable for severe convective weather pattern development. After initializing available numerical weather prediction model outputs (i.e., MM5, NGM, ETA, NOGAPS, BKFG, etc.), examine the graphical representations of the NWP model outputs to determine which model has the best handle on the current synoptic weather pattern.

Use examples of the classic convective patterns described later in this section to determine which, if any, apply to the current weather pattern (regime). If there is a match, apply information regarding storm characteristics, triggers, timing, and outbreak areas to the forecast. Table 3-5 suggest products and features to look for in developing a forecast for severe convective weather. Notice that jets, shears, moisture gradients, and dry-air intrusions are key features on these products.

Pay close attention to areas where favorable severe convective storm predictors stack with height. The more favorable conditions in a specific area, the greater the chance of development of severe thunderstorms.

Use composite products to help stack significant features. If most of the predictors indicate a "strong" potential for severe weather, then seriously consider forecasting severe thunderstorms, tornadoes, strong winds, and/or hail. If predictors mostly indicate "weak," consider forecasting non-severe thunderstorms. If indicators are mixed, consider forecasting non-severe thunderstorms with isolated or scattered severe thunderstorms. Finally, if low-level predictors are strong, weak upper-level diffluence is often sufficient to trigger severe weather, and if low-level predictors are marginal, strong upper-level diffluence is necessary to trigger severe convective storms.

Incorporate local rules of thumb, the Military Weather Advisory, forecast discussion bulletins, and the various stability indices appropriate for the location into the decision-making process. It is seldom wise to base a forecast on a single tool when several are available.

2. Forecast Products and Techniques. Begin with a Skew-T diagram of the nearest representative upper-air sounding to the location of interest. Use the techniques described to analyze the sounding for indications of convective instability in the air mass. There are many good Skew-T software programs available (SHARP, RAOB, Skew-T Pro, etc.), to help with this analysis. Determine if the air mass is absolutely unstable or, more commonly, conditionally unstable.

Next analyze the upper-air and surface products for the area of interest (Table 3-5). Upper-air analyses are not as useful for forecasting air-mass thunderstorms as they are for forecasting the classic trackable severe thunderstorms previously discussed, but they can often help. The LAWC will play a key role in an analysis since it can be updated hourly and the significant triggering mechanisms are often apparent on these products. Table 3-6 identifies key predictors to analyze and why they are significant.

3. Identifying Severe Weather Features.

a. Tornado Features. The first requirement to predict tornadoes is a forecast for severe thunderstorms, and then to determine whether tornadogenesis will occur. Research has shown the strength or magnitude of various parameters derived from the low-level wind and thermodynamic fields of the atmosphere are keys to tornadogenesis. The elements that contribute to tornadogenesis are strong storm-relative flow, strong vertical wind shear, strong low-level vorticity (i.e., strong low-level

Table 3-5. Product analysis matrix and reasoning.

Charts	**Feature to Analyze**	**Why** (favorable/unfavorable; weak, moderate, strong chance for severe weather conditions.)
200 mb/300 mb	Identify jet maximums.	• ≤55 knots **Weak**
		• 56 to 85 knots **Moderate**
		• ≥ 86 knots **Strong**
	Streamline and identify diffluent areas.	Favorable for development.
	Shade areas of horizontal wind speed shear.	Favorable for development.
500 mb	Identify jet maximums.	• ≤ 35 kt **Weak**
		• 36 to 49 **Moderate**
		• ≥ 50 **Strong**
	Streamline and identify diffluent areas.	Favorable for development.
	Shade areas of horizontal wind speed shear.	• ≤ 15 kt **Weak**
		• 16 to 29 kt **Moderate**
		• ≥ 30 kt **Strong**
	Isopleth 12-hour height falls (Oct to Apr) or 24-hour height falls (May to Sep).	• ≤ 30 m **Weak**
		• 31 to 60 m **Moderate**
		• ≥ 61 m **Strong**
	Perform 2°C isotherm analysis, color cold pools, identify thermal ridges and troughs.	Severe activity suppressed near and east of thermal ridge particularly when in phase with streamline ridge.
	Identify areas of cold air advection.	The following temperatures are favorable:
		• Dec to Feb: -16°C or lower.
		• Mar, Apr, Oct, Nov: -14°C or lower.
		• May, Jun: -12°C or lower.
		• Jul to Sep: -10°C or lower.
	Identify dew-point depressions of 6°C or less, moisture analysis.	Cut-off moisture sources indicate a short wave is present.
	Identify areas of vorticity advection.	NVA: **Weak Or Not Favorable.**
		Positive Vorticity isopleths crossing 500-mb height contours:
		• ≤ 30° **Moderate**
		• > 30° **Strong**
		Storms develop on the periphery of the vorticity maximum and not directly below.
700 mb	Perform 2° isotherm analysis, identify thermal troughs and ridges.	Good stacking of cold air here and at 500 mb is favorable for severe.
	Indicate (12-hour) temperature no-change line.	Advancement of the temp. no-change line ahead of the 700-mb trough indicates the surface low will intensify.
	Draw dew-point depression lines.	Moisture fields detached from the main moisture field indicate rising motions and a possible short wave in the area.
	Mark dry line. The dry line can be placed where dew point is ≤ 0°C, the dew point depression is ≥ 7°C, or the RH is ≤ 50 percent.	Weak winds across the dry line: **Weak**
		Winds 15 to 25 knots crossing between 10° and 40°: **Moderate**
		Winds ≥ 26 knots crossing between 41° and 90°: **Strong**
	Streamline and identify confluent areas.	Confluent areas are favorable for severe.

Table 3-5. (cont) Product analysis matrix and reasoning

Charts	**Feature to Analyze**	**Why** (favorable/unfavorable; weak, moderate, strong chance for severe weather conditions).
850 mb	Streamline and identify confluent zones.	The greater the angle of winds from dry to moist air, the more unstable.
	Identify wind speed maximums.	• ≤ 20 knots **Weak** • 21 to 34 knots **Moderate** • ≥ 35 knots **Strong**
	Draw every 2ºC isotherm starting with an isotherm that bisects the entire U.S. Mark thermal ridges.	Thermal ridge is often ahead of convergence zone. Cold air advection often found behind the main convergence zone, unless a dry line forms and moves out ahead of the cold advection. (Warm air is usually ahead of the main convergence zone).
	Draw isodrosotherms every 2ºC starting at 6ºC (43ºF).	Dew point: • < 8ºC (46ºF) **Weak** • 9ºC to 12ºC (48 to 54ºC) **Moderate** • ≥ 13ºC (55ºF) **Strong**
	Color in areas of significant moisture.	A diffuse moisture field is unfavorable for development of severe weather. Thermal ridge east of moisture axis: **Weak** Thermal ridge coincident with the moisture axis: **Moderate** Thermal ridge west of the moisture axis: **Strong**
	Identify dry line.	Note the angle of winds crossing from dry to moist air, the greater the angle, the greater the instability. Where the dry line is intruding into moist areas is unstable.
Surface	2-mb isobar analysis	Surface pressure patterns indicate likely areas for severe weather: • > 1009 mb **Weak** • 1009 to 1005 mb **Moderate** • < 1005 **Strong**
	Isallobaric analysis (12-hour) identify areas of falling pressure.	Squall lines often develop in narrow troughs of falling pressure. A strong pressure rise/fall couplet is favorable for severe weather. The following values indicate probability of severe weather: • ≤ 1 mb **Weak** • 2 to 5 mb **Moderate** • > 6 mb **Strong**
	Identify areas of rapid temperature and dew point change	Favorable for development of severe weather
	2º isodrosotherm analysis starting at 50ºF (10ºC).	Areas of horizontal moisture convergence are favorable. The following dew point temperatures indicate probability of severe weather: • ≤ 50ºF (10ºC) **Severe Unlikely** • > 51 to 55ºF (11 to 12ºC) **Weak** • > 56 to 64ºF (13 to 17ºC) **Moderate** • > 65ºF (18ºC) **Strong**
	Identify confluent streamline areas.	Areas of strong winds converging with weak winds is favorable.
	Identify highs, lows, fronts, squall lines, and dry lines and mark their previous locations.	Any discontinuity line is a likely place for thunderstorm development. Intersecting discontinuity lines are highly probable locations for development. Use distance between past and current locations to extrapolate onset of thunderstorms.
1000/500 mb Thickness	Mark thickness ridge.	Probable area for squall line.
	Mark thickness no-chance line (12-hour).	Indicates area of cold advection.

Table 3-6. Identifying features of airmass thunderstorm development on upper-air charts.

Product	**Feature to Analyze**	**Why** (favorable/unfavorable for convective weather conditions.)
200 mb/300 mb	Streamline	Areas under diffluent flow aloft are favorable for thunderstorms; convergence strongly suppresses development.
500 mb	Ridge placement	Convection forms on the confluent side of the ridge axis.
	Vorticity advection	PVA is present, severe weather is possible.
		NVA or neutral, severe weather unlikely
	Short-wave troughs	Severe weather possible.
850 mb/925 mb	Streamline	Confluence.
	Gradient Winds	Use to forecast steering flow if stronger than forecast sea breeze.
Surface/LAWC	Streamline: Draw convergent asymptotes	Expect convection to begin along these lines when convective temperature is reached.
Composite Workchart	Satellite depiction Radar observations LAWC: streamlines	Identify cells/lines of convection. Identify intersecting boundaries as possible areas for severe winds, heavy rain, and possible hail.
	Mark past positions of significant features.	Use the time difference and distance between related weather features to forecast their future movement, and to forecast areas of intersecting boundaries and development.

cyclonic circulation), potential for strong rotating updrafts, and great instability or buoyancy. All of these elements are associated with supercells, which are known tornado producers. However, not all tornado-producing thunderstorms are supercells.

Several tools are available for determining whether conditions exist for tornadogenesis. These are shown in Table 3-7 with the parameters they measure, and what each tool is used to predict. The actual threshold values are listed in Tables 3-2 through 3-4.

Note that several of these tools indicate storm type rather than just tornado type or strength. Knowing the expected storm type can indicate where tornadoes are likely to form within the storm, aiding severe storm metwatch: Combine storm-type knowledge with the WSR-88D's meso indicator (and other features), track and forecast movement of potentially tornadic storms and radar signatures. Listed below are descriptions of likely locations where supercell and non-supercell tornadoes are found in a storm.

Table 3-7. Tornado forecasting tools.

Tool	**Parameter(s) Measured**	**Indicator for:**
Bulk Richardson Number (BRN).	Buoyancy and wind shear.	Storm type: multicell, supercell.
Convective Available Potential Energy (CAPE).	Buoyancy.	Potential updraft strength, which relates to storm intensity.
Energy/Helicity Index (EHI).	Combines CAPE and SRH.	Tornadoes.
Mean Storm Inflow (MSI).	Storm relative winds.	Mesocyclone development.
Storm Relative Directional Shear (SRDS).	Low-level vorticity (i.e., strong low-level cyclonic circulation).	Mesocyclone development.
Storm Relative Helicity (SRH).	Potential for a rotating updraft, horizontal vorticity due to wind shear.	Supercells and tornadoes.
Hodographs.	Vertical and horizontal directional and speed shear, mean wind, storm motion, storm inflow, helicity.	Storm type: single cell, multicell, and supercell.

(1) Supercell Tornadoes. These tornadoes develop in the mesocyclone of classic and heavy precipitation supercells, and on the leading edge of the storm updraft in the vicinity of the wall cloud of low-precipitation supercells.

(2) Non-super-cell Tornadoes. They can occur in the flanking line of a supercell, during the growth stage in the updraft of "pulse" thunderstorms (strong, single-cell storms), along the gust front of multicellular storms, and in strong updraft centers of multicellular storms. Tornadoes in single-cell and multicellular storms are rare, and require exceptionally strong development of those storms to produce a tornado.

b. Bow Echo Features. The bow echo is a line of storms that accelerates ahead of the main line of storms. The bow echo forms from strong thunderstorms with a gust front. A strong downburst develops and the line echo wave pattern (LEWP) begins to "bow." A well-developed bow echo or "spear head" is associated with the mature stage of the downburst. Strong winds and tornadoes are possible near the bow.

As the downburst weakens, the line forms a comma shape often with a mesocyclone developing on the north end of the comma which will be evident by a "hook" in the radar echo. At this point, tornadoes may still occur in the area of the mesocyclone, but the winds are now decreasing. Figure 3-13 shows the evolution of the bow echo in a LEWP. Strong to severe straight-line winds are likely to exist if four specific characteristics of the bow echo are present (see Figure 3-14).

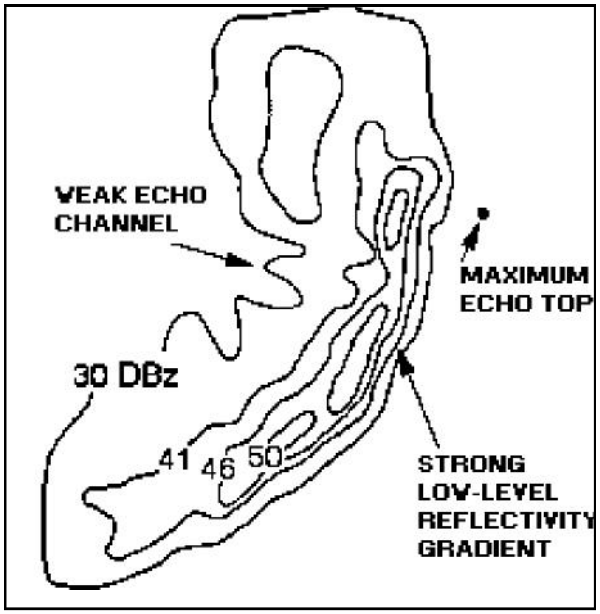

Figure 3-14. Bow Echo. Strong winds and tornadoes are possible near the bow.

- Weak echo channels exist.

- The low-level echo configuration is concave downstream (bowed).

- A strong reflectivity gradient along the leading edge of the concave-shaped echo.

- The maximum echo top is over or ahead of the strong low-level reflectivity gradient.

c. Wet Microburst Features. Microbursts or downbursts are difficult to predict and detect due to their small spatial scale (less than 4-km diameter), shallow vertical extent and short life span. However,

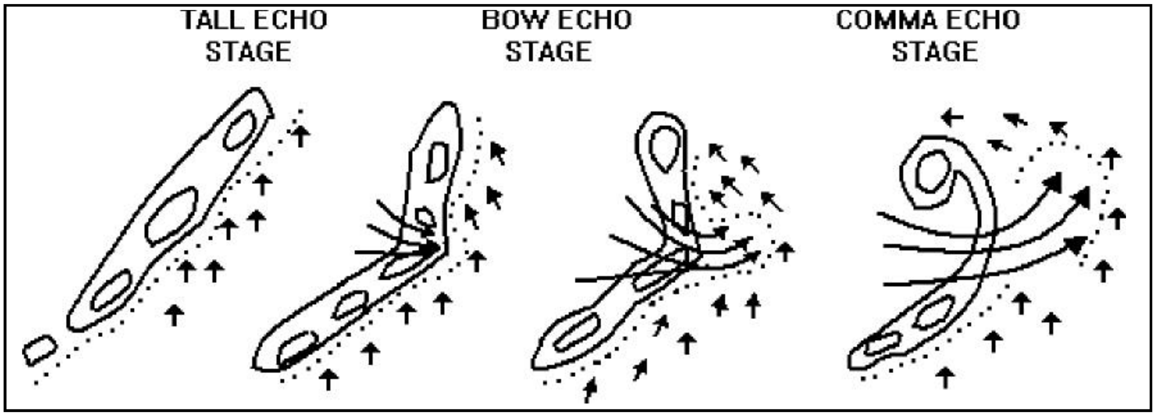

Figure 3-13. Line Echo Wave Pattern, Bow Echo Evolution. Strong to severe straight-line winds are likely to exist.

the following technique can provide up to 40 minutes lead time predicting maximum downburst winds from pulse-type thunderstorms. The following conditions must exist:

- A source of dry (dew-point depression ≥ 18°C), potentially cold air between 400 and 500 mb.
- Maximum Reflectivity at least 55 dBZ (sufficient moisture for entrainment of the parcel to produce negative buoyancy through evaporative cooling).

To predict the wind gust potential:

- Interrogate the suspect storm cells on the WSR-88D.
- Obtain the maximum top of the cell using Echo Tops and get the VIL.
- Cross-reference the two values using Table 3-8, and read the maximum downburst winds, in knots, in the body of the table.

For the Southern Plains, Southeast, and Gulf Coast, add 1/3 of the mean low-level wind speed to the value in the table to predict the wind gust from the potential microburst. For the Northeast, add mean low-level wind speed to the value given in the table.

Note This technique will not work when VIL values are large due to hail contamination. When thunderstorms are too close to the radar, echo top estimates are erroneously low. This technique also works poorly for thunderstorms over 125 NM away from the radar. This only works for pulse-type air-mass thunderstorms, it does not work for multicell and supercell storms.

d. Boundaries and Boundary Interaction Features.

(1) Satellite. As diurnal heating occurs, cumulus clouds will often form into cloud streets (over land) oriented with the gradient wind flow. Look for clear areas forming in the flow; these identify sea-breeze fronts, lake breezes, and outflow boundaries. The leading edge of these boundaries between clear areas and the cloud streets is highly favorable for development. Similarly, the boundary between cloud-free areas and fog-stratus broken/overcast areas are prime for development as clouds burn off. When outflow boundaries intersect, convection is almost guaranteed if the air mass is unstable or conditionally unstable.

Table 3-8. Wet microburst potential table. Determine VIL and maximum cell tops (100s feet) from WSR-88D, to read maximum downburst winds (knots) in body of table.

		TOPS									
		250	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**
	35	45	42	37	31	23					
	40	49	46	42	38	30	19				
	45	53	50	47	42	36	28	14			
V	**50**	57	55	51	46	41	34	24			
I	**55**	60	57	54	50	45	39	31	18		
L	**60**	63	61	57	54	50	44	37	27		
	65	66	64	61	58	53	48	42	33	21	
	70	69	67	64	61	57	53	46	39	29	
	75	72	70	67	64	60	56	50	44	35	22
	80	75	72	70	67	63	59	54	48	40	29

(2) Radar - WSR-88D. Sea-breeze boundaries and other discontinuities in low-level flow can usually be identified in the WSR-88D base reflectivity displays. The sea breeze will appear as a thin line of low intensity returns parallel to the coastline. These patterns can be entirely obliterated if lower intensity values are masked for clutter suppression. Convection is most likely to form on these lines when convective temperature is reached.

(3) Streamline Analysis/Sea Breeze Onset. Use the latest LAWC streamline analysis combined with current satellite and radar analysis. Create a composite product (or use the LAWC) to identify locations of streamline-confluent asymptotes, sea/lake breezes, and outflow boundaries. Mark past placements of these boundaries. Determine speed and direction of movement of boundaries to project when and where these boundaries will intersect. The intersections are almost certain to result in air-mass thunderstorms. If thunderstorms are present along the boundaries already, severe weather (usually severe wind gusts) is possible. Tornadoes and hail are unlikely unless strong upper-level support is evident.

(4) MWA Products. These centrally produced products cover large forecast areas and periods of time. Although they are not site-specific forecasts, they are products of an extensive evaluation of observed and forecast weather conditions. They should be carefully considered in the preparation of site-specific thunderstorm forecasts. They should not be used as the sole decision aid in preparing the forecast.

4. Techniques

a. Severe Thunderstorm Checklist. The parameters involved in producing ordinary versus severe thunderstorms are well documented. However, no two thunderstorm situations are alike. There are varying degrees of intensity for each parameter, and the combinations of parameters produce individual storm events. This makes a foolproof, all-inclusive checklist nearly impossible. The following checklist is an outline of the forecast-reasoning process. Incorporate local rules of thumb and stability thresholds to fine-tune this for each station.

Step 1. Identify the current weather regime.

- Dryline.
- Frontal.
- Overrunning.
- Cold Core.
- Squall Line.
- Air-mass Thunderstorm.

Step 2. Analyze available NWP models. Tailor the analysis.

Step 3. Are elements for severe weather present? Refer to Table 3-5 for features conducive severe weather.

Step 4. Analyze current and forecast Skew-Ts and calculate stability indices appropriate for the weather pattern and station. Do they indicate severe weather potential? See Tables 3-6 and 3-7.

Step 5. Produce and examine the current and forecast hodograph from current and forecast sounding data. What type of storms can be expected?

Step 6. What type of severe weather: tornadoes, convective winds, or hail? Severe weather forecasting aids follow.

b. Forecasting Convective Wind Gusts. This section presents four methods to forecast convective wind gusts. Each is designed to forecast winds under different conditions: Use the T1 method for scattered thunderstorms in the vicinity of the forecast location; T2 winds are designed for intense squall lines or numerous thunderstorms; the next method is for high-based thunderstorms; and the Snyder Method is for air-mass or pulse thunderstorms. Each of these methods requires a current sounding or forecast Skew-T.

(1) T1 Gust Computation. There are two methods of computing the T1 gust, one for when an inversion is present, the other for no inversion.

Table 3-9. T1 convective gust potential.

T1 values (°C)	Average Gust Speed (knots)	T1 values (°C)	Average Gust Speed (knots)
3	17	15	49
4	20	16	51
5	23	17	53
6	26	18	55
7	29	19	57
8	32	20	58
9	35	21	60
10	37	22	61
11	39	23	63
12	41	24	64
13	45	25	65
14	47		

(a) T1 Method 1. The top of the inversion present is within 150 mb to 200 mb of the surface and is not susceptible to being broken by surface heating.

- Project moist adiabat from warmest point of inversion to 600 mb.

- Calculate temperature difference (°C) between the moist adiabat and the dry-bulb temperature trace at 600 mb (label as T1).

- Refer to Table 3-9. The value found for T1 is considered to be the average gust speed.

- Add 1/3 of lower 5,000 feet mean wind speed to chart value for maximum gust speed.

- Wind gust direction is determined from mean wind direction in layers between 10,000 feet and 14,000 feet above local terrain.

(b) T1 Method 2. No inversion present or inversion is relatively high (more than 200 mb above surface).

- Forecast maximum surface temperature.

- Project moist adiabat from maximum temperature to 600 mb.

- Calculate the difference between the moist adiabat and dry-bulb temperature trace at 600 mb and label as T1.

- Refer to Table 64. The value found for T1 is considered to be the average gust speed.

- Add 1/3 of lower 5,000 feet mean wind speed to chart value for maximum gust speed.

- Wind gust direction is determined from mean wind direction in layers between 10,000 and 14,000 feet above local terrain.

(2) T2 Gust Computation.

Step 1. Find the wet-bulb zero (where wet-bulb curve crosses the 0°C isotherm).

Step 2. Project the moist adiabat through wet-bulb zero to the surface.

Step 3. Read value of temperature (°C).

Step 4. Subtract the moist adiabat temperature (°C) from surface dry-bulb (°C) (or projected maximum) temperature.

Step 5. Label as T2.

Step 6. Refer to Figure 3-15. Follow the T2 to where it intersects the three curves. The first

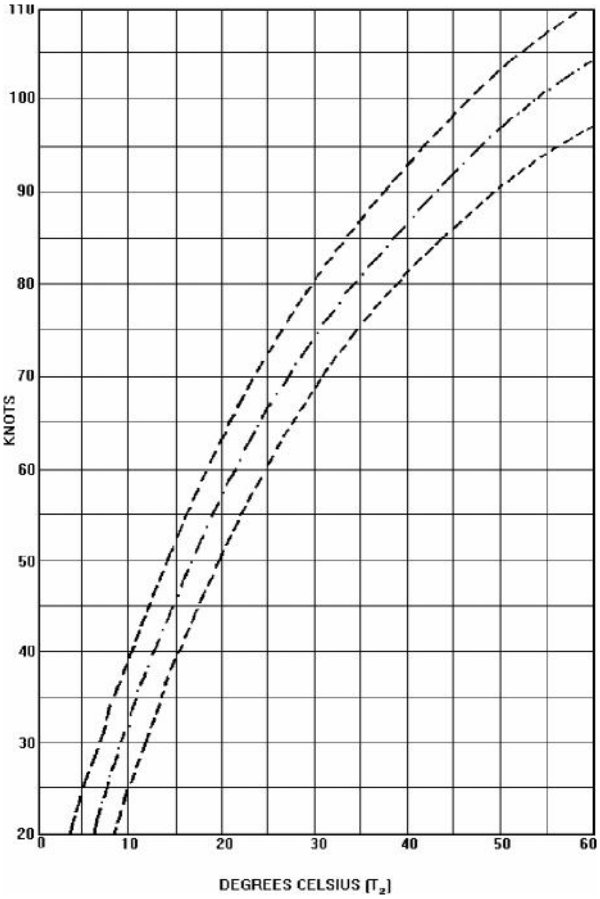

Figure 3-15. T2 Gust Computation Chart. See Step 6.

intersection point represents the minimum gust in knots; the middle intersection point represents the average gust; and the upper intersection point represents the maximum gust.

Step 7. The mean wind direction in the layer between 10,000 and 14,000 feet has been found to closely approximate direction of maximum gusts at surface and should be used in forecasting gust direction.

(3) High-based Thunderstorm Method. This method was developed for use near the Rocky Mountains to determine the potential for wind gusts reaching the surface, produced by high-based thunderstorms (typically 17,000 to 18,000 feet MSL). This method can be adapted for other mountainous regions as long as the atmosphere above 12,000 feet is convectively unstable and low levels are dry.

Step 1. Multiply 500-mb dew-point depression by three and subtract 700-mb dew-point depression from the result. If number is negative, proceed; if number is positive, gust potential is zero.

Step 2. Compute upper-level instability index (UI) by lifting a parcel from 500 mb to its LCL, then up moist adiabat through 400 mb to 300 mb. At the point where the moist adiabat crosses 300 mb and 400 mb, read the temperature and use the following formula:

$$UI = (T_{400} - T_{500}) + (T_{300} - T_{500})$$

where: T_{300} is the temperature at which the moist adiabat crosses the 300 mb level. T_{400} is similar, at the 400 mb level. T_{500} is temperature of sounding at 500 mb level.

Step 3. Using Figure 3-16, plot the result of Step 1 and 2. If the point falls within:

Area 1. Conditions are too moist for strong convective gusts, even though thunderstorms may occur.

Area 2. Conditions are too stable for upper-level thunderstorms.

Area 3. The potential exists for gusts greater than 30 knots for period during which thunderstorms are expected.

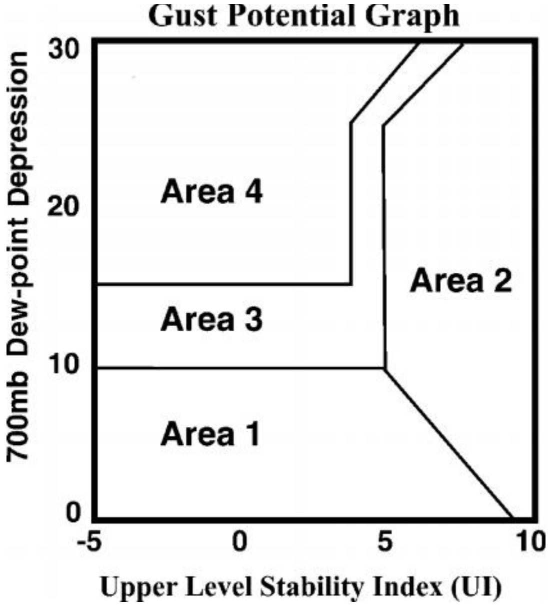

Figure 3-16. Gust Potential Graph. Plot the result of Step 1 and 2.

Area 4. The potential exists for gusts greater than 40 knots for period during which thunderstorms are expected.

(4) Snyder Method. A method of forecasting the average gust with air-mass thunderstorm.

Step 1. Plot the latest rawinsonde, plot the wet-bulb curve, and locate the height of wet-bulb zero (SHARP is good for this). _______

Step 2. Forecast max temperature (°F) at time of thunderstorm occurrence _______

Step 3. Lower the WBZ value to the surface, moist adiabatically, to calculate the "Down Rush Temperature (°F)." - _______

Step 4. Step 2 - Step 3. _______

Step 5. Find the average wind speed in the layer 5,000 feet above and below the WBZ. + _______

Step 6. Average gust associated with air-mass thunderstorms. Ignoring units, add Step 4 + Step 5. _______ knots

(5) Derecho Checklist. The derecho resembles the Line Echo Wave Pattern (LEWP) and/or a large bow echo. Storm movement can exceed 50 knots and move slightly to the right of the mean wind. They last for several hours, continually maintaining high wind speeds and gusts, and traverse hundreds of miles. The following parameters are necessary for derecho development. Without all of these elements present, derechos are unlikely.

- Surface-based Lifted Index (SBLI) ≤ -6.
- Warm air advection at 850 mb and 700 mb.
- Quasi-stationary boundary parallel to 500-mb flow.
- Maximum 500-mb 12-hour height-falls ≥ 60 meters.
- Estimated mean wind speed from 8,000 to 18,000 feet ≥ 25 knots.
- Mean relative humidity from 700 mb to 500 mb less than 70 percent.
- 500-mb flow direction from west to northwest (most frequent with wind direction 240° to 280°).

Finally, if these parameters exist over a 250 NM (or greater) swath downstream of the MCS, then any rapid-moving squall lines or squall line segments moving with the mean flow of 35 knots or greater are likely to develop into a derecho. If these conditions do not persist downstream for 250 NM, locally strong or severe winds are still possible in lines of downburst clusters, or bow echoes.

c. Forecasting Hail and Hail Size. Hail is a micro-scale phenomenon associated with all thunderstorms. The key is to determine if the hail within a thunderstorm will occur at the surface, and then determine the hailstone size.

(1) Forecasting Hail (Using Skew-T). The following is an objective method derived from a study of severe Midwest thunderstorms. This method determines the cloud depth ratio, then correlates cloud depth ratio and freezing level to occurrence or non-occurrence of hail.

Step 1. From a Skew-T, calculate the Convective Condensation Level (CCL), Equilibrium Level (EL), and Freezing Level (FL).

Step 2. Determine cloud-depth ratio:

$$\frac{(\text{CCL - FL})}{(\text{CCL - EL})}$$

Step 3. Cross-reference the cloud-depth ratio (y-axis) to the freezing level (x-axis) on Figure 3-17. If the plot is below the line, forecast hail; if above the line, do not forecast hail.

(2) Forecasting Hail Size (Using Skew-T). The following technique requires a sounding plotted on a Skew-T chart. The calculations are accomplished graphically, either on the Skew-T or on the accompanying charts (Figures 3-18 to 3-20).

Step 1. Determine the convective condensation level (CCL), which is found using the mean mixing ratio in the lowest 150 mb, then follow

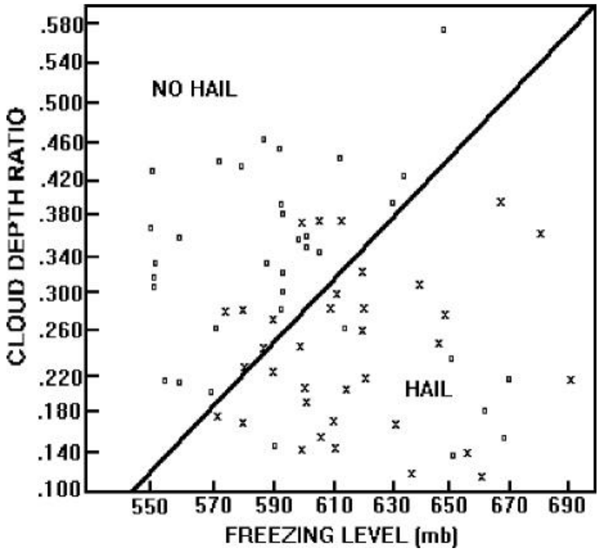

Figure 3-17. Hail Prediction Chart. See text. Also shown are the results of the original study.

the saturation mixing-ratio line to its intersection with the temperature trace, Point A (see Figure 3-18).

Step 2. Point B_H is at the intersection of the –5°C isotherm and the sounding.

Step 3. From Point A go moist adiabatically to the pressure at B_H, this is Point B'.

Step 4. Note the temperature difference (°C) between B_H and B'. It is used with the horizontal axis in Figure 3-19.

Step 5. Go from B_H dry adiabatically to the CCL; this is Point H'. The temperature difference between B_H and H' is used with the vertical axis in Figure 3-19.

Step 6. Forecast preliminary hail size from Figure 3-19. The dashed lines on Figure 3-19 represent hailstone diameter in inches.

Step 7. Use the following procedures to find the wet-bulb-zero height.

- Choose a reported level close to the freezing level. From the dew point at that level, draw a line upward parallel to a saturation mixing-ratio line.

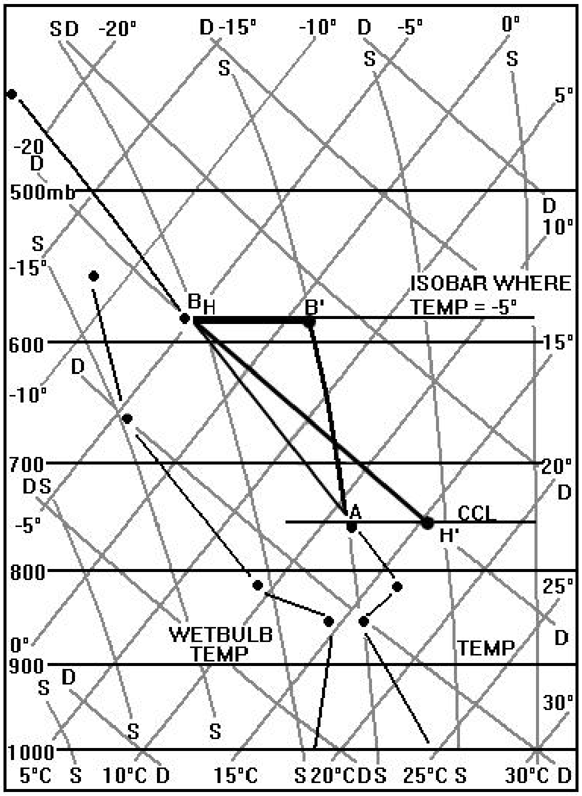

Figure 3-18. Skew-T Chart. Curves labeled "S" are saturation adiabats; lines labeled "D" are dry adiabats. Other points are described in the text.

- From the temperature at the same level, draw a line upward parallel to a dry adiabatic until it intersects the line drawn in previous step.

- From this intersection, follow a saturation adiabat back to the original pressure. This is the wet-bulb temperature (°C).

- Repeat the above steps as necessary; connect the various wet-bulb temperatures to form a trace.

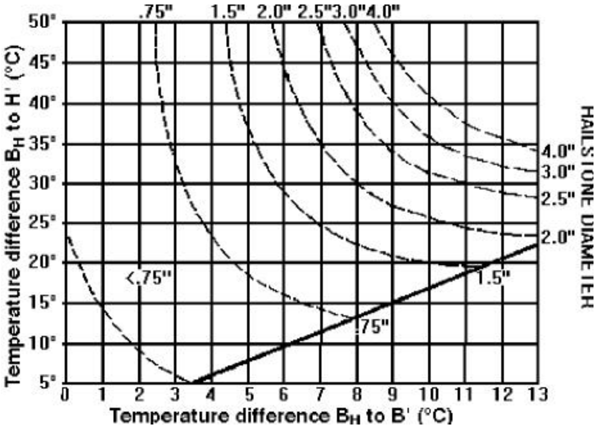

Figure 3-19. Preliminary hail size nomogram.

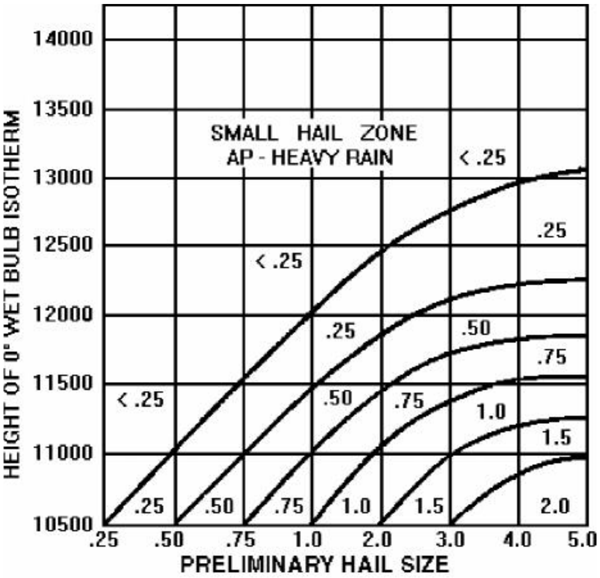

Figure 3-20. Final Hail Size Nomogram. If the wet-bulb-zero height is greater than 10,500 feet, enter this figure with the preliminary hail size and the height of the wet-bulb-zero to compute final hail size.

- Wet-bulb-zero height is the height at which the wet-bulb trace crosses the 0°C isotherm.

Step 8. If the wet-bulb-zero height is less than 10,500 feet, the preliminary hail size computed in Step 6 will be the final size. If the wet-bulb-zero height is greater than 10,500 feet, enter Figure 3-20 with the preliminary hail size and the height of the wet-bulb-zero to compute final hail size.

(3) Forecasting Hail Size Using VIL Density. Use the WSR-88D to approximate hail size from active storms using Table 3-10.

5. General Rules of Thumb.

a. Onset of Typical Thunderstorms. Predict thunderstorm onset at the time when convective temperature is needed or maximum solar insolation is expected. Predict formation along confluent streamline asymptotes and discontinuities in the flow such as sea breezes, outflow boundaries, and lake breezes.

b. Severe Thunderstorms. Hail, tornadoes, and severe winds are less common with air-mass thunderstorms. For severe storms to occur, at least one of the following must be present:

Table 3-10. VIL density versus hail size.

VIL Density	Hail Size
≥ 3.5 g/m^3	≥ ¾ inch
≥ 4.0	≥ 1 inch
≥ 4.3	≥ Golf ball size

- Cold and/or dry air aloft.
- Positive Vorticity Advection.
- Shortwave troughs at 500 mb.

Note: Low-level convergence is necessary for severe weather.

6. Regional Rules of Thumb.

a. Convective Weather: Alaska. Use the following rules of thumb to aid in forecasting convective weather in Alaska.

- Use critical values for stability indices in Table 3-11 to help base thunderstorm forecasts.
- The temperature at the top of air-mass thunderstorms should be below –28°C to produce lightning.
- Do not forecast air-mass thunderstorms (thunderstorms not directly associated with a front) if the wind at 500 mb exceeds 20 knots. Strong winds at 500 mb, in air masses not associated with fronts, tend to shear cloud tops of developing air-mass thunderstorms before they produce lightning.
- Thunderstorms over Alaska develop along trough lines (90 percent of the time), which coincide with lines of "thermal convergence" on the surface analysis. Though thunderstorms are often shallow on the early 1500Z surface analysis, these trough

Table 3-11. Stability indices for Alaska.

INDEX	CRITICAL VALUE
KI	≥ 20
VT	30.0 after 15 May 29.0 after 1 Jun 27.0 after 15 Jun 26.5 after 1 Jul 26.0 after 15 Jul 27.0 after 15 Aug 28.0 after 1 Sep

lines can often be detected by analyzing the product with 2-mb spacing.

b. Convective Weather: Europe and Eastern Mediterranean. Because of the diversity of climates found in this region (only a few of which compare to those in the U.S.), the standard methods used to forecast thunderstorms in the U.S. need to be modified to be effective in convective weather forecasting in this region.

For example, although a typical Midwestern thunderstorm is over 30,000 feet tall, in the United Kingdom (UK), thunder can come from a 12,000-foot high convective cell, and hail frequently falls from rain showers (TCU/CU) in the UK. Nevertheless, several useful forecasting methods, stability indices, and rules of thumb have been developed to assist in forecasting convective weather for Europe and the Mediterranean.

For European locations north of 40°N, spring and summer is the favored thunderstorm season. The lack of thunderstorm activity here during the colder months of the year is primarily due to lack of solar insolation. The central part of the Commonwealth of Independent States (CIS) and eastern Europe experience most convective activity in the spring. Increased solar heating of the landmass and fronts that still frequent the region causes this. Locations in North Africa appear to have a relatively "flat" annual distribution of thunderstorm activity. The Mediterranean and eastern Turkey have two maxima, one in spring and another in fall. In the southeast Mediterranean, the thunderstorm season occurs from fall through spring when polar and arctic air passes over the warm Mediterranean waters.

(1) Modified Stability Indices. The most successful stability indices for Europe are summarized in Table 3-12. The KO Index is generally considered the most effective—it was designed specifically for Europe. It has advantage over the other two because it considers data below 5,000 feet, and it includes moisture at all levels. Other stability indices as they pertain to Europe and the eastern Mediterranean are described below.

(a) Showalter Stability Index (SSI). Though it does not reflect all anomalies below 850 mb, it has a high success rate.

(b) Total Totals (TT) Index. Used widely in both the US and Europe, it is available to forecasters via trajectory forecast bulletins. Since it fails to consider low-level moisture, it tends to under-forecast convection in Europe.

(c) Gollehon Stability Index (GSI). This index was developed specifically for use in the Mediterranean, and has proven reliable.

Table 3-12. Summary of stability indices for Europe.

INDEX	REGION	CRITICAL VALUE	
KO	Europe	> 6	No Thunderstorms
		2 to 6	Thunderstorms Possible
		< 2	Severe Thunderstorms Possible
SSI	Europe	< 2	Thunderstorms
TT	Europe	> 42	Thunderstorms Possible
		> 48	Thunderstorms Vicinity
		> 50	Thunderstorms in TAF
GSI	Mediterranean	≤ 8	Thunderstorms
		> 8	No Thunderstorms
S	Europe, April-September only	< 39	No Thunderstorms (89 percent)
		41 to 45	Thunderstorms Possible (42 percent)
		> 46	Thunderstorms Likely (75 percent)
Wet-bulb Potential Temperature at 850 mb	Europe, spring and summer	≥ 16°C	Strong chance Thunderstorms

Table 3-13. GMGO thunderstorm severity chart. Enter table with cloud-top temperature (A) and/or extent of cloud above freezing level (B); read across to predict severity. Use less severe condition if the table parameters disagree.

A. Cloud-Top Temp (°C)	B. Extent Above Freezing Level (1000 ft)	Event (Old AIRWAYS Code)	Precip (mm)	Visibility Rain (km)	Visibility Snow (km)	Hail (cm)	Peak Gust (kt)
–10 to –15	5 to 7	RW–	< 1	> 8	3 to 6		< 20
–15 to –20	7 to 9	RW	1 to 2	6 to 8	1 to 3		20 to 25
–20 to –25	9 to 12	RW+	2 to 3	4 to 6	0.5 to 1		25 to 30
–25 to –35	12 to 17	TRW–	3 to 5	3 to 4	< 0.5		30 to 35
–35 to –45	17 to 22	TRW	5 to 10	2 to 3		< 1	35 to 45
–45 to –55	22 to 27	TRW+	10 to 30	1 to 2		1 to 4	45 to 60
–55 to –70	27 to 35	TRW++	30 to 100	< 1		4 to 10	60 to 100

(d) S Index (S). Created by the German Military Geophysical Office (GMGO), it's a variation of the Total Totals (TT) index.

(e) Wet-bulb Potential Temperature at 850-mb. Threshold values that have worked for Europe are listed. A study by Bradbury of the UK Met Office indicates that the wet-bulb potential temperature value at 850 mb of 16°C or higher is a strong indicator of thunderstorms in Europe (spring and summer).

(2) Severe Thunderstorms. In the Mediterranean region, techniques in AWS-TR 200, *Notes on Analysis and Severe-storm Forecasting Procedures of the AFGWC*, work well. Anywhere else in Europe, they over-forecast thunderstorms.

The GMGO developed a technique based on the vertical extent of convective clouds and the height of the freezing level (Table 3-13). This technique works very well in the predominantly maritime air masses north of the Alps. The following provides a relatively simple, reasonably accurate, consistent method for forecasting thunderstorm severity in this European region.

- Begin with a sounding. RAREPs, PIREPs, and the MWA are additional sources.
- Find the cloud-top temperature and the extent of cloud above the freezing level.
- Move across Table 3-13 to derive the most probable condition that will occur.

Note: The result is the worst case. Use the less severe of "A" or "B" if there is a discrepancy.

(a) Rules of Thumb.

1. Central Europe. Easterly flow isn't always dry in central Europe. Persistent low-level flow from the east/southeast often brings low-level moisture from the Mediterranean. Surface dew points and 850-mb and/or 925-mb products should be watched carefully for increasing moisture moving in from the east/southeast.

2. North and Central Europe. Spring and summertime severe thunderstorms in central and northern Europe are frequently associated with above-normal surface temperatures.

c. Convective Weather: Korea. Triggers for thunderstorms include orographic lift, frontal lift, and/or surface heating. Refer to Table 3-14 for stability indices considered critical for thunderstorm formation in Korea. Below are some of the necessary parameters needed for convective weather in Korea.

- Significant diffluence aloft.
- Abundant low-level moisture.
- Cold air advection at 500 mb.
- 500-mb temperature of –20°C or less.

Table 3-14. Critical Stability index values for Korea.

INDEX	CRITICAL VALUE
TT	≥ 50
SSI	≤ –1
LI	≤ –1

d. Convective Weather: WSR-88D Guide for Tropical Weather. In Guam, the NWS discovered for tropical regions, cells should extend at least to the –30°C level, and VIL values should be greater than or equal to 20 kg/m^2 to be considered a thunderstorm. Close to and far away from the radar, echo tops and VIL values always decrease, but reflectivities (dBZ) with thunderstorms tend to hold the strongest values in the middle levels. Values greater than or equal to 40 dBZ above the –10°C height, and composite reflectivity values of 45 dBZ to over 50 dBZ, are other very good indicators.