Mesoscale Meteorology

4   Convective Dynamics

In this chapter we cover a broad range of phenomena associated with moist atmospheric convection: single- and multi-cell thunderstorms, squall lines, bright bands, bow echoes, mesoscale convective complexes, supercell storms, and tornadoes.

4.1   Introduction to Thunderstorms / Moist Atmospheric Convection

4.1.1   Considerations

- classifying the various types of storms

- necessary conditions for their existence

- large-scale organization

- feedback to environment

- dynamics

- factors that control movement and rotation

- prediction

4.1.2   Definition

A thunderstorm is a local storm, invariably produced by a cumulonimbus cloud, that always is accompanied by lightning and thunder. It usually contains strong gusts of wind, heavy rain, and sometimes hail.

4.1.3   Climatology

At any given time there are an estimated 2,000 thunderstorms in progress around the Earth, mostly in tropical and subtropical latitudes. Globally, around 45,000 thunderstorms take place each day. Annually, about 16 million thunderstorms occur around the world, of which approximately 100,000 are experienced in the United States.
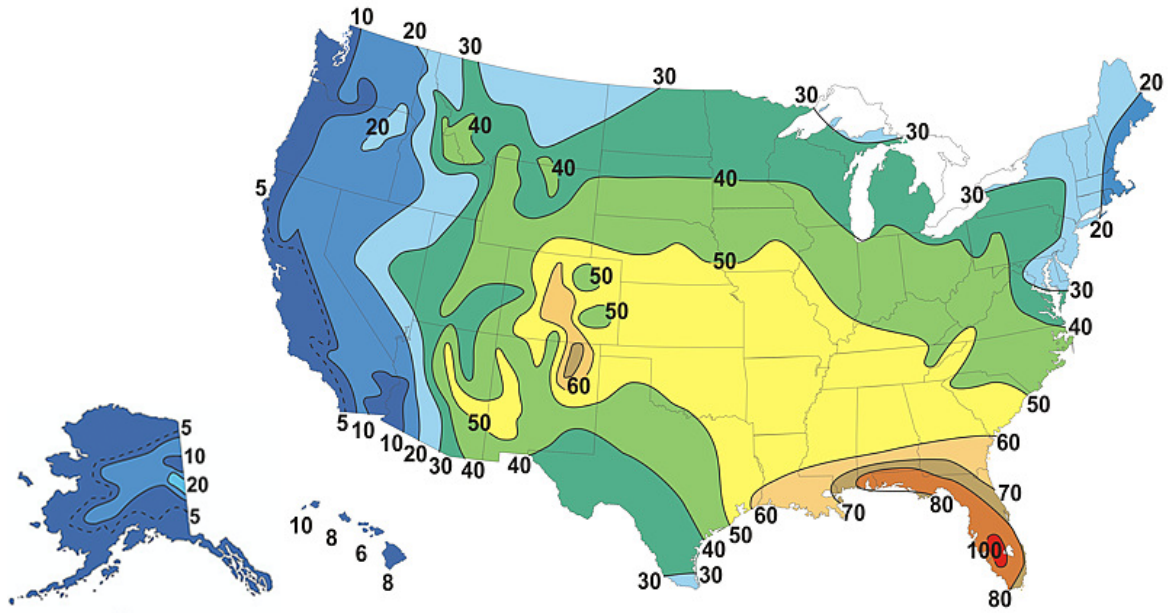
Figure 1: Average number of thunderstorm days each year throughout the U.S. [Credit: NWC]
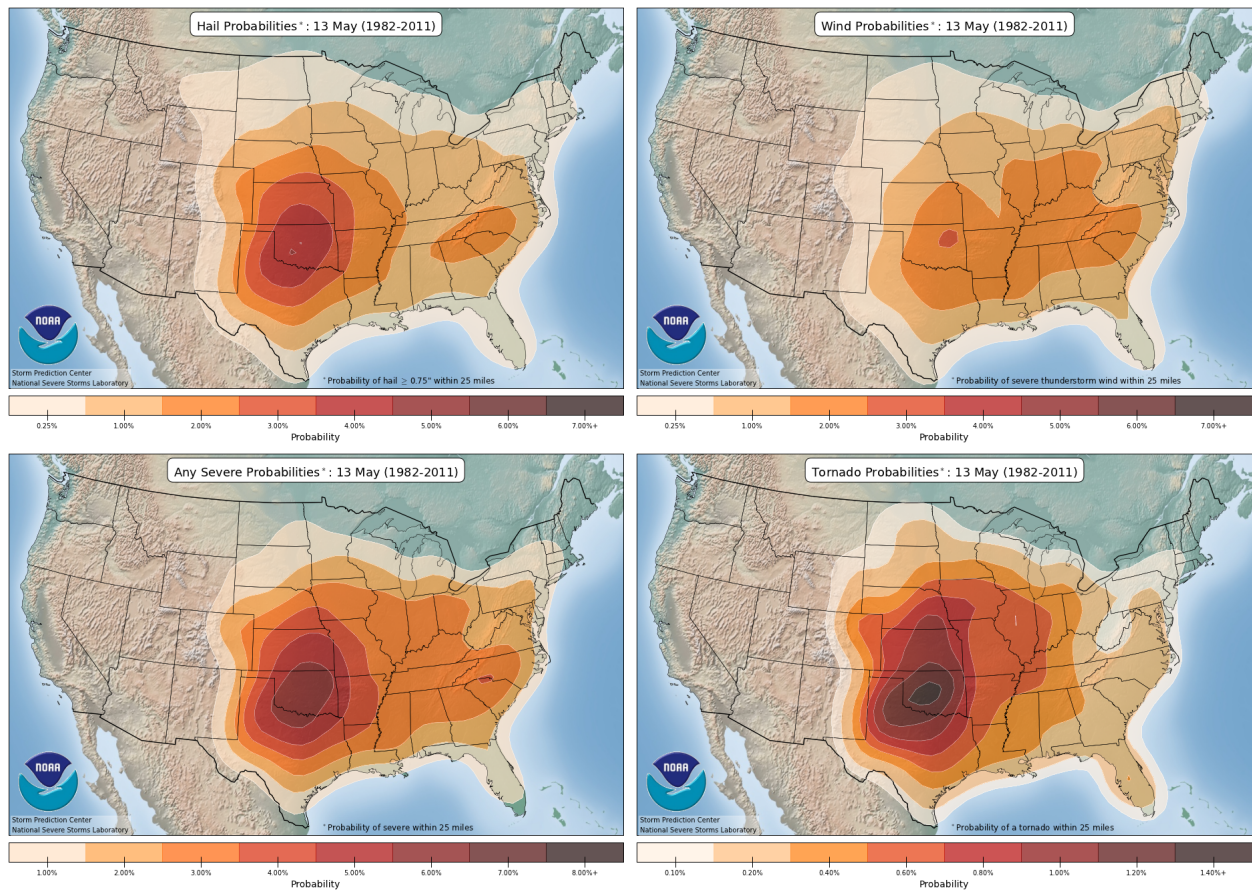

Figure 2: Climatological probabilities of several severe weather categories. [Credit: SPC]

4.1.4 Modes of Convection / Storm Classification

Although a continuous spectrum of storms exists, meteorologists find it convenient to classify storms into specific categories according to their structure, intensity, environments in which they form, and weather produced.

- **Single-cell or air-mass storm**

  Typically lasts 20-30 minutes. Pulse storms can produce severe weather elements such as downbursts, hail, some heavy rainfall and occasionally weak tornadoes.

- **Multi-cell cluster storm**

  A group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle. Multicell storms can produce moderate size hail, flash floods and weak tornadoes.

- **Multi-cell line (squall line) storm**

  Consist of a line of storms with a continuous, well developed gust front at the leading edge of the line. Also known as squall lines, these storms can produce small to moderate size hail, occasional flash floods and weak tornadoes.

- **Supercells**

  Defined as a thunderstorm with a rotating updraft, these storms can produce strong downbursts, large hail, occasional flash floods and weak to violent tornadoes.
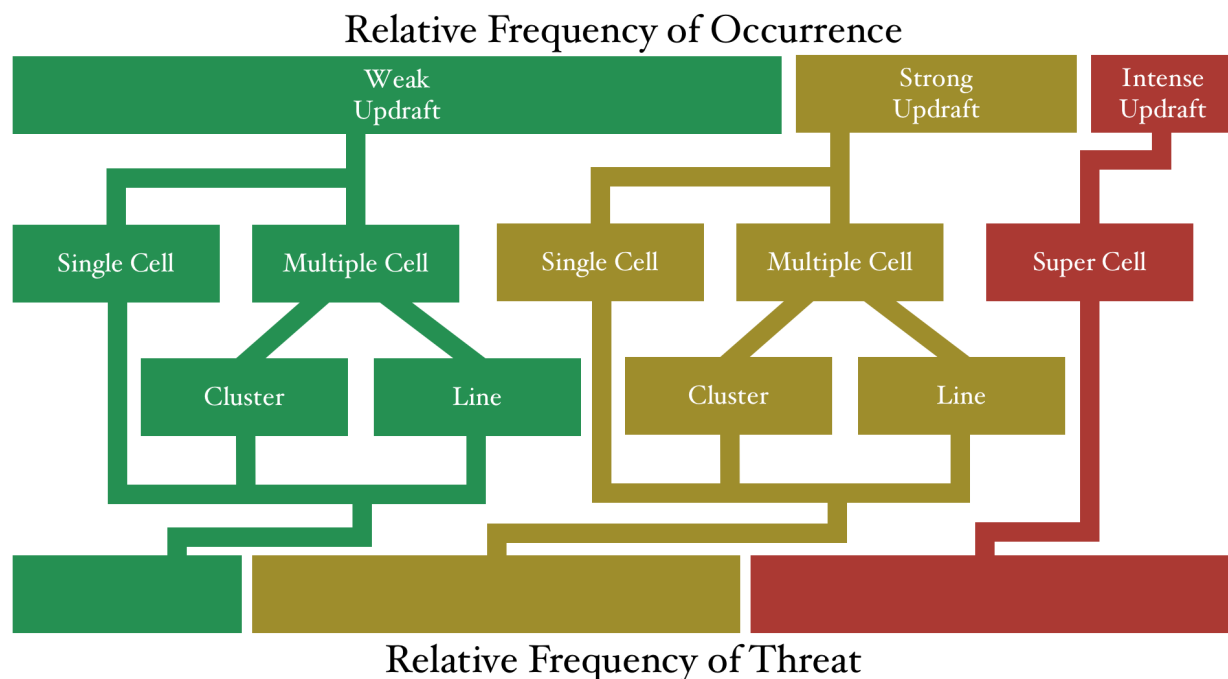

Figure 3: Thunderstorm spectrum

4.1.5 Basic Dynamics

- **Convection**

  transport of fluid properties by motions within that fluid.

  Note: Meteorologists often use the word "convection" to describe such storms in a general manner, though the term convection specifically refers to the motion of a fluid resulting in the transport and mixing of properties of the fluid. To be more precise, a convective cloud is one which owes its vertical development, and possibly its origin, to convection (upward air currents).

- **Buoyancy**

  vertically oriented force on a parcel of air due to density differences between between the parcel and surrounding air.

The effect of buoyancy is seen by considering the perturbation vertical momentum equation.

$$\underbrace{\frac{dw}{dt}}_{\substack{\text{vertical}\\\text{acceleration}}} = \underbrace{-\frac{1}{\overline{\rho}}\frac{\partial p^{'}}{\partial z}}_{\substack{\text{pressure gradient}\\\text{force}}} + \underbrace{g\frac{\theta^{'}}{\overline{\theta}}}_{\substack{\text{thermal}\\\text{buoyancy}}} + \underbrace{0.61gq_v^{'}}_{\substack{\text{vapor}\\\text{buoyancy}}} - \underbrace{gL}_{\substack{\text{liquid water}\\\text{loading}}} \quad , \tag{1}$$

where L is the combined liquid and ice water content.

4.1.6 Key Ingredients for Thunderstorms

Convective Available Potential Temperature (CAPE)

- CAPE measures the amount of convective instability, or more accurately the potential energy of an environmental sounding – the energy that can be converted into kinetic energy when an air parcel rises from the level of free convection to the equilibrium level

- It is based on simple parcel theory which neglects the effect of mixing/friction, PGF, and sometimes water loading (Eqn. 1 becomes $dw/dt = B$, where B represents to combined buoyancy terms).

- From CAPE, we can estimate the maximum vertical velocity that can be reached by a parcel.

The CAPE is computed as follows, starting with the vertical equation of motion (having neglected friction, PGF, and water loading)

$$\frac{dw}{dt} = B \rightarrow \frac{d}{dt}\left(\frac{w^2}{2}\right) = Bw = B\frac{dz}{dt} \rightarrow d\left(\frac{w^2}{2}\right) = Bw = Bdz$$

Clearly, the lefthand side is the change in kinetic energy associated with vertical ascent of dz on the righthand side. When $B > 0$ ($T_{\text{parcel}} > T_{\text{env}}$), the force is directed upward and the kinetic energy increases.

The total amount of kinetic energy increase is equal to the work done by B. This is represented by integrating both sides with respect to z from the level of free convection (LFC) to the equilibrium level (EL)

$$\int_{\text{LFC}}^{\text{EL}} \frac{d}{dz}\left(\frac{w^2}{2}\right) dz = \int_{\text{LFC}}^{\text{EL}} B dz = \text{CAPE}$$

$$w_{\text{EL}}^2 - w_{\text{LFC}}^2 = 2\text{CAPE}.$$

Typically, the vertical velocity at the LFC is nearly zero, and thus the maximum updraft (at the EL) is

$$w_{\text{EL}} \approx \sqrt{2\text{CAPE}}$$

.

CAPE is depicted on a Skew-T diagram as the positive area where the air parcel temperature is warmer than the environment (see Fig. 4). It may be increased by an increase in surface temperature, an increase in low-level moisture, or a cooling in the mid-levels of the atmosphere.

Other related physical parameters include

- **Lifted Index (LI)**

  temperature excess in 500 mb environment over that of a parcel lifted from the low 'moist' layer (negative value indicates instability)

- **Lifting Condensation Level (LCL)**

  the height at which the relative humidity (RH) of an air parcel will reach 100% when it is cooled by dry adiabatic lifting.

- **Level of Free Convection (LFC)**

  level at which a parcel is warmer than the environment

- **Equilibrium Level (EL)**

  level at which a parcel becomes the same temperature as the environment again

- **Convective Inhibition (CIN)**

  The "negative area" on a thermodynamic diagram in the layer where a parcel is colder than the environment.

  It is defined as the amount of energy beyond the normal work of expansion need to lift a parcel from the surface to the Level of Free Convection (LFC).

Skew-T analysis and parcel theory typically neglect the effect of PGF induced by vertical motion, essentially assuming that the environment is unchanged by the parcel motion. They also neglect the effect of mixing/friction and water loading. Therefore, parcel theory tends to overestimate the intensity of the updraft. Still, it provides a useful upper limit for the convection intensity.
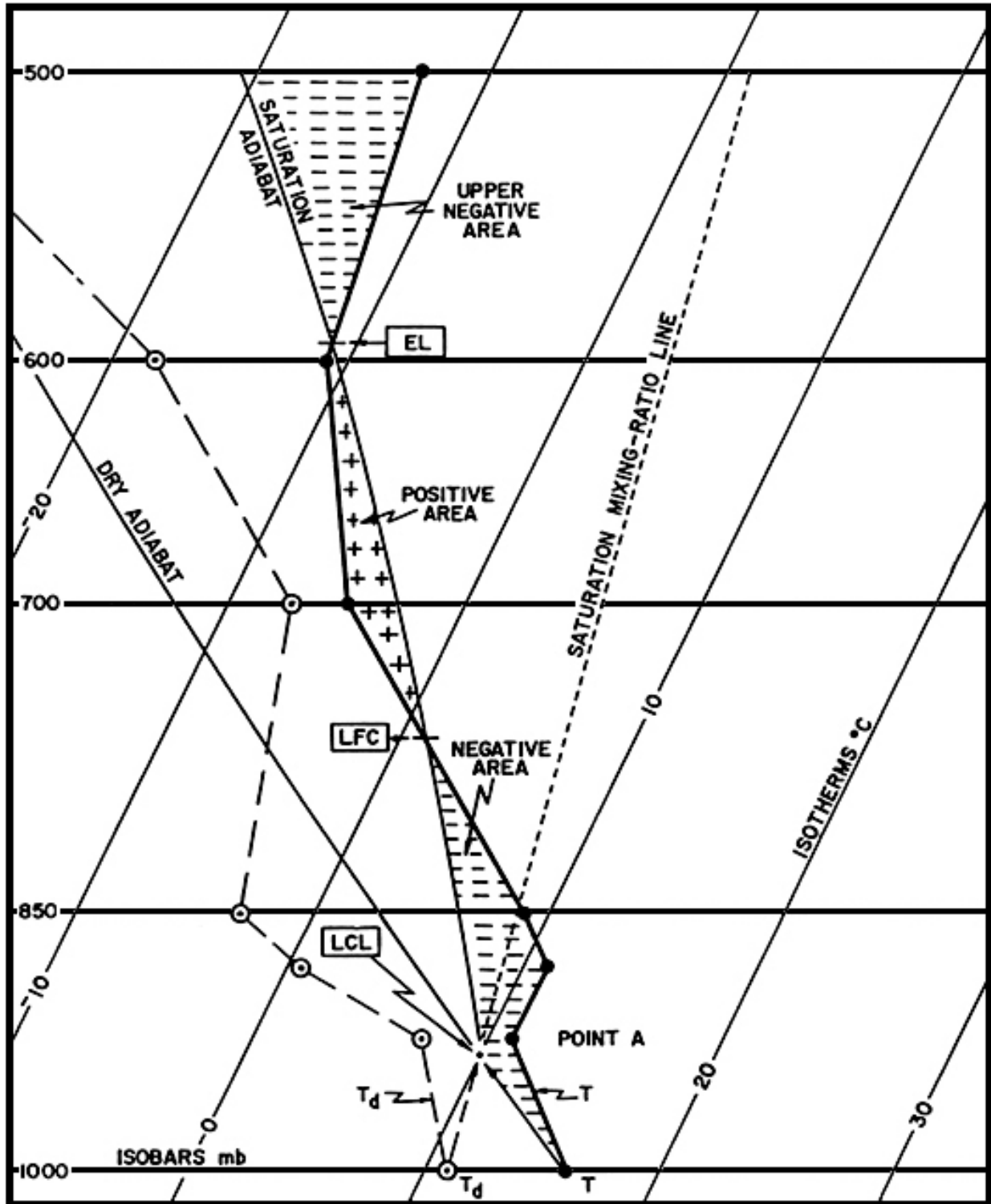
Figure 4: Skew-T diagram.

Vertical Wind Shear

Vertical wind shear describes the change in wind speed and/or direction with height. Severe storms need strong veering of the wind with height and a strong increase in speed.

Vertical environmental wind shear (along with CAPE) is one of the most important factors in determining storm type. Numerical models have been very effective tools to aid our understanding of such effects. The general relationship between vertical environmental wind shear and storm classification is shown in Fig. 5.
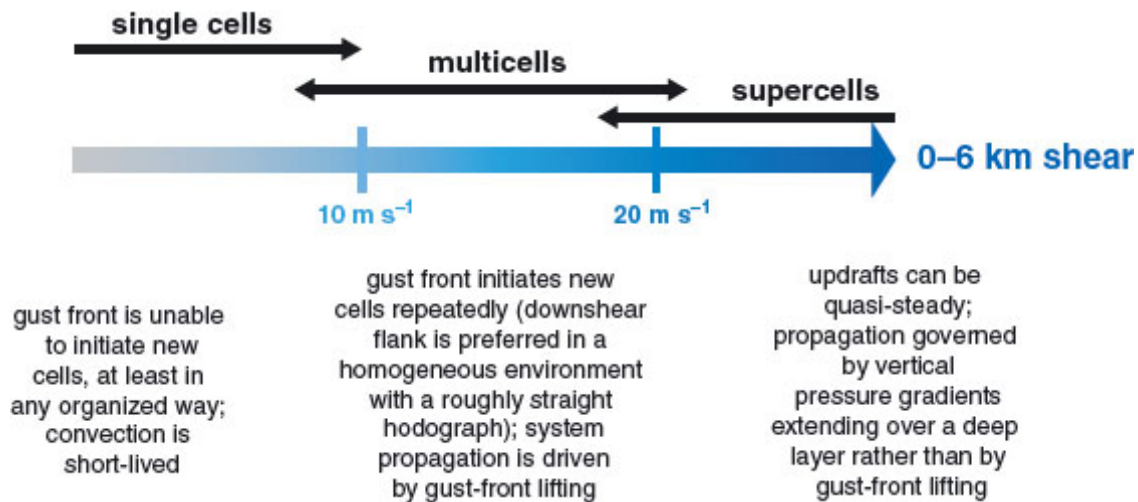

Figure 5: Spectrum of storm types as a function of vertical wind shear. The relationship between vertical wind shear magnitudes and the nature of cell regeneration/propagation is also shown. [From Markowski and Richardson]

Mechanism to Trigger Instability

In order for deep moist convection to initiate, a mechanism is needed to exploit (or trigger) the enviromental instability. Examples include: front, terrain, dryline, daytime heating, and landuse inhomogeneities.

4.1.7 Predicting Thunderstorm Type

The *Bulk Richardson Number* (BRN) is a measure of the relative importance of environmental instability effects to environmental shear effects:

$$\text{BRN} = \frac{\text{CAPE}}{\text{S}^2} \quad \text{where} \quad \text{S}^2 = 0.5(\overline{U}_{6000 \text{ m}} - \overline{U}_{500 \text{ m}})^2.$$

In this context, the BRN essentially represents the ratio of kinetic energy of the updraft to the kinetic energy of the inflow (the denominator is really the storm-relative inflow kinetic energy, sometimes called the BRN shear). Large values are associated with single-cell storms, while smaller values ($\sim$ 10-20) are associated with supercells. The BRN must be used with caution, however. If CAPE and shear are both relatively small, one can still get "supercell" values of BRN, even though storms will be weak (if they form at all).

4.2 Single-Cell Storms

Single-cell storms were first studied after World War II, motivated by many commercial and military aircraft accidents. At the time, the newly developed radar was exploited for weather studies. One such study was The Thunderstorm Project. That study resulted in thee first observation of the life cycle of a thunderstorm. These storms are also known as air-mass, ordinary, or garden variety storms.

4.2.1 General Characteristics

- Consists of a single cell (updraft/downdraft pair).

- Forms in an environment characterized by large conditional instability, warm moist air near the ground, and weak vertical shear.

- Vertically erect $\rightarrow$ built-in self-destruction mechanism.

- Can produce strong straight-line winds or microburst.

- Life cycle is generally < 1 h, usually 30-45 min.

- These storms form in weakly-forced environments, and are driven primary by convective instability rather than the ambient winds.

- They are some times called "air-mass" storms because they form within air-masses with more-or-less horizontal homogeneity.

4.2.2 Life Cycle

Cumulus Phase

- development of towering cumulus

  - region of low level convergence
  - warm moist air
  - updraft driven by latent heating

- nearby cumulus may merge to form a much larger cloud

- dominated by updraft
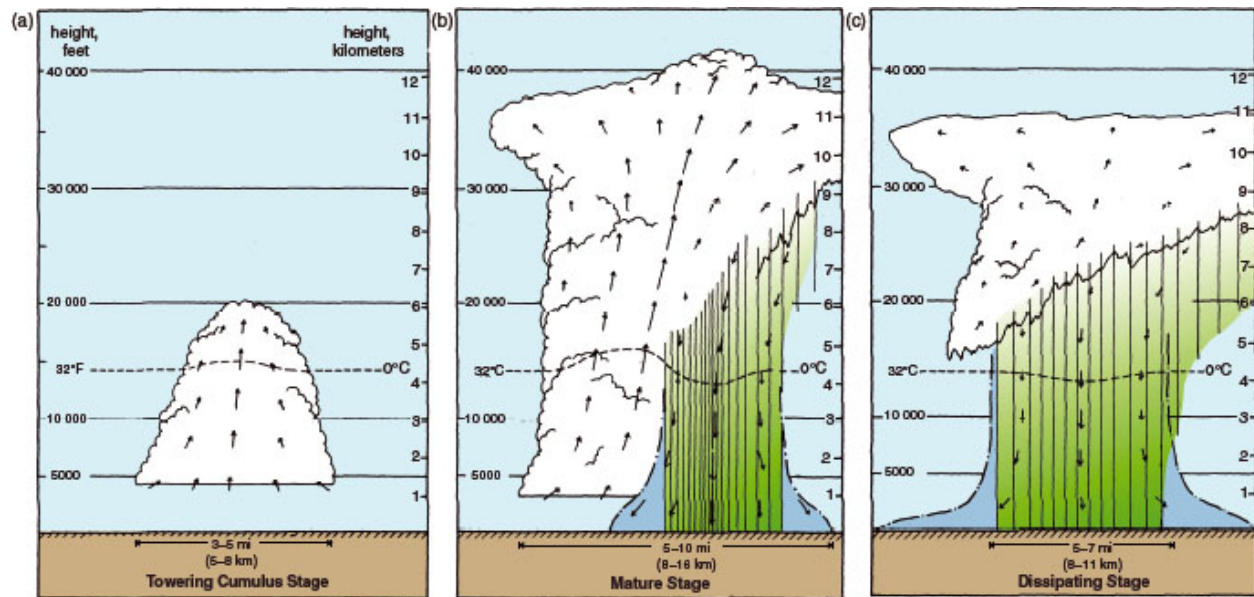
- mixing and entrainment occur in the updraft

Figure 6: The three stages of an ordinary cell: (a) towering cumulus or developing stage, (b) mature stage, and (c) dissipating stage. [From Markowski and Richardson]

Figure 7: Stages in the life of an ordinary-cell convective storm. (Top left) Cumulus congestus stage; (top right) maturing stage; (second row, left) mature stage; (second row, right) dissipating stage [Bluestein 2013]

Mature Phase

- precipitation, typically heavy and perhaps containing small hail, begins to reach the ground.

- the precipitation drags some of the surrounding air down creating the downdraft.

- the mature phase represents the peak intensity of the storm.

- updrafts and downdrafts are about equal in strength.

- gusty winds result from the downdraft spreading out on the ground.

- the anvil, or cloud top, begins to turn to ice, or glaciate.

Dissipating Phase

- eventually the downdraft overwhelms the updraft and convection collapses because the cloud is vertically-oriented.

- precipitation becomes lighter and diminishes.

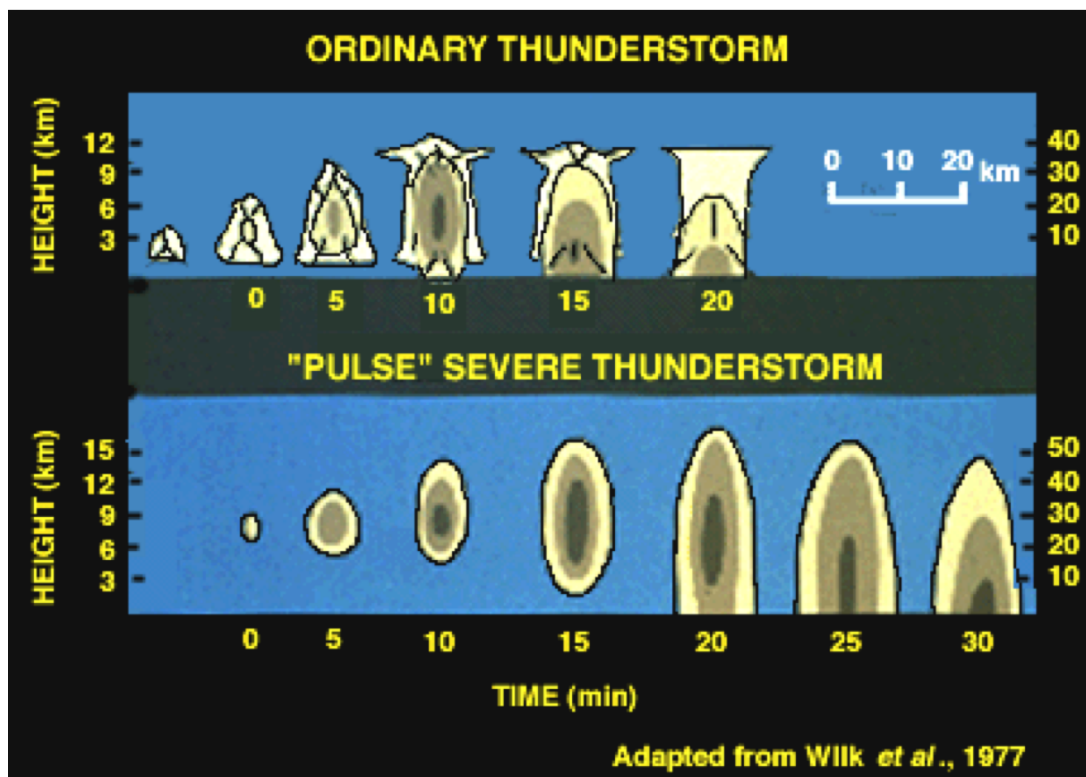- the cloud begins to evaporate from the bottom up, often leaving behind an "orphan anvil."

Figure 8: Visual and radar lifecycle of an ordinary-cell convective storm. [From Bluestein 2013]

4.2.3 Development and Decay of a Single-Cell Storm

- In the absence of frontal or other forcing, daytime heating of the PBL causes the convective temperature to be reached. Thus, there is no 'negative area' (CIN) on the skew-T diagram for an air parcel rising from the surface - the lid is broken.

- Updraft forms - once the air reaches the LCL, latent heat is released due to condensation ($Ldq_v = c_p dT$)

- For every 1 g/kg of water condensed, the atmosphere warms about $3°$. This feeds into the buoyancy term through an increase in θ' (Eq. 1). The saturated air parcel ascends following the moist adiabat, along which the equivalent potential temperature θ_e is conserved.

- Until the EL is reached, the air parcel is warmer than the environment, which keeps the buoyancy positive (without the effect of water loading).

- When a cloud forms, some of it is carried upward by the draft and some moves out of the updraft. The 'weight' of this liquid water makes the air parcel heavier, this 'water loading' effect acts to reduce the positive buoyancy.

$$B = g(\theta'/\overline{\theta}) \qquad\qquad -gL$$
$$10 \times 3/300 \qquad\qquad -10 \times 0.01 \text{ kg/kg}$$

Therefore, 10 g/kg of cloud or rain water will offset a 3 K temperature surplus.

- When the cloud grows to a stage that the updraft becomes too 'heavy' because of water loading, it will collapse and the updraft then turns into a downdraft.

- Another important process that contributes to the collapse is evaporative cooling. When a cloud grows, cloud droplets turn into larger rain drops that fall out of the updraft, reaching the lower level where the air is sub-saturated. The rain drops will partially evaporate in this sub-saturated air, producing evaporative cooling. This cooling enhances the downdraft.

- In the absence of vertical wind shear, the cell is upright, and this downdraft would then disrupt the low-level updraft, causing the cell to dissipate. This is the built-in self-destruction mechanism mentioned earlier.

- The cold downdraft sometimes forms a cold pool that propagates away from the cell above, further removing the lift underneath the cell.

4.2.4 Entrainment

- entrainment is the process by which saturated air from the growing cumulus cloud mixes with the surrounding cooler and drier (unsaturated) air.

- Entrainment causes evaporation of the exterior of the cloud and tends to reduce the upward buoyancy there.

4.2.5 Impact of the Pressure Gradient Force

- In addition to buoyancy force and water loading, another force that is also acting on the rising parcel is the vertical pressure gradient force (PGF)

- When an air parcel rises (due to buoyancy), it has to push off air above it, creating higher pressure (positive $p^{'}$) above (imagine pushing yourself through a crowd)

- Below the rising parcel, a void is created (imagine a vacuum cleaner), leading to lower pressure at the cloud base
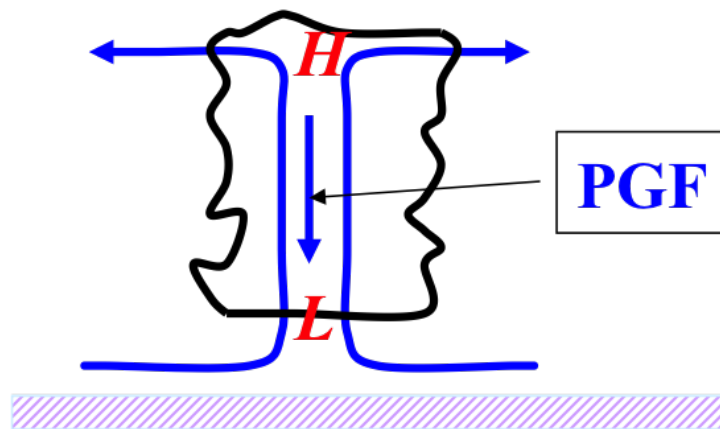

Figure 9: Conceptual diagram of the pressure gradient force associated with a single-cell storm.

- The higher pressure above will push air to the side, making room for the rising parcel, while the lower pressure below attracts surrounding air to compensate for the displaced parcel.

- Such a positive-negative pattern of $p^{'}$ creates a downward pressure gradient. The PGF force therefore opposes the buoyancy force and acts to reduce the net upward forcing.

- The degree of opposition to the buoyancy force depends on the aspect ratio of the cloud (L/H), or more accurately of the updraft.

- The effect is larger for wider/large aspect-ratio cloud, and weaker for narrower/small aspect ratio cloud, because

  - For a narrow cloud, a small amount of air has to be displaced/attracted by the rising parcel, therefore the p perturbation needed to achieve this is smaller, so that the opposing pressure gradient is smaller (often $\ll$ B) so a narrow cloud can grow faster.
  - PGF is stronger for wider clouds, and as a result, the net upward force (B - PGF) is significantly reduced, the cloud can only grow slowly. When B and PGF have similar magnitude, the vertical motion becomes quasi-hydrostatic. This is typical of large scale broad ascent.

- Dynamic stability analysis of inviscid flow shows that infinitely narrow clouds grow the fastest, but in reality, the presence of turbulent mixing prevents the cloud from becoming too narrow, hence the typical aspect ratio of clouds is ~ 1.

4.2.6 Downbursts and Microbursts

Downbursts are defined to have horizontal dimensions less than 10 km. Downbursts are produced by a downdraft, by definition. If a downburst is particularly small in its horizontal dimensions, it is also known as a microburst.

A *microburst* is an anomalously strong, concentrated downdraft that produces a pocket of dangerous wind shear near the ground over an area of 4 km or less in horizontal extent. These classifications are based rather arbitrarily on horizontal scales rather than on the governing dynamics
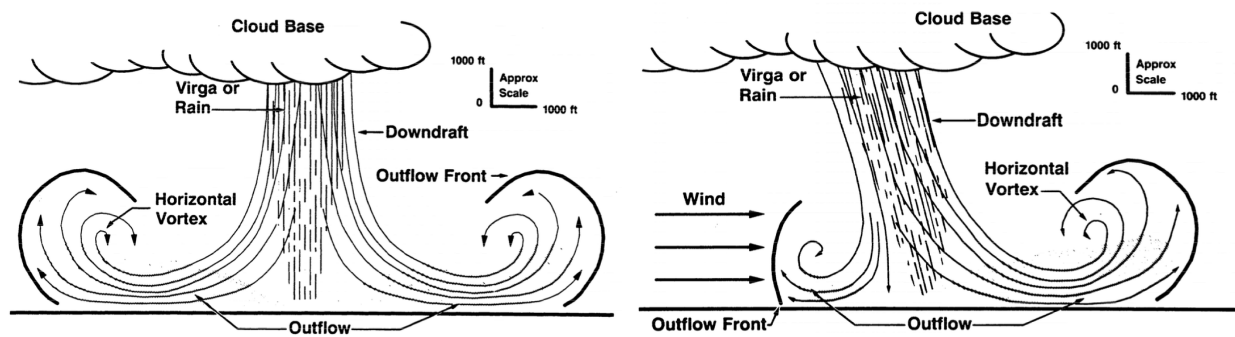

Figure 10: Diagram of a symmetric (left) and asymmetric (right) microburst. [Credit: FAA]

Microbursts are generally short-lived (3-8 min), small, and isolated (city block). Microbursts are associated with cumulonimbus clouds and can be accompanied by heavy rain (wet) or vanishing sprinkles (dry).
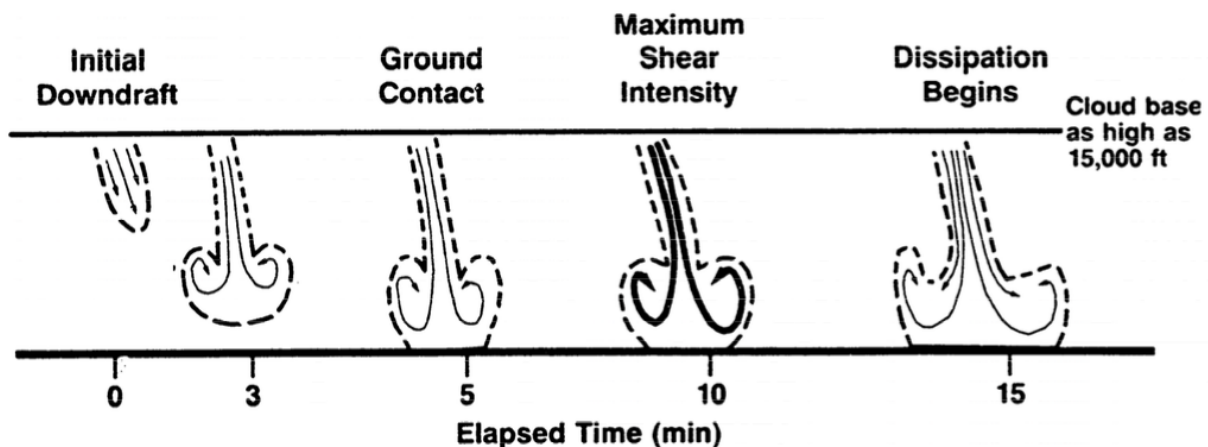

Figure 11: Evolution of a microburst. Winds typically intensify for about 5 min after ground contact and dissipate after 10-20 min. [Credit: FAA]

Dry Microbursts

- A microburst with little or no precipitation.

- Very dry air is located beneath the cloud base.

- Hydrometeors falling into the dry air will evaporate causing a pool of cold air just below cloud base.

- This cold pool descends rapidly forming the dry microburst.

- Often you can't detect them until it is too late.

Wet Microbursts

- Microbursts associated with moderate or heavy precipitation.

- Some dry air above cloud top gets entrained in the top of the thunderstorm.

- This dry air mixes with cloud air causing some evaporation of the cloud.

- Evaporational cooling will form a pool of cold air near the top of the cloud.

- This cold pool descends and adds to the downdraft to form a microburst.

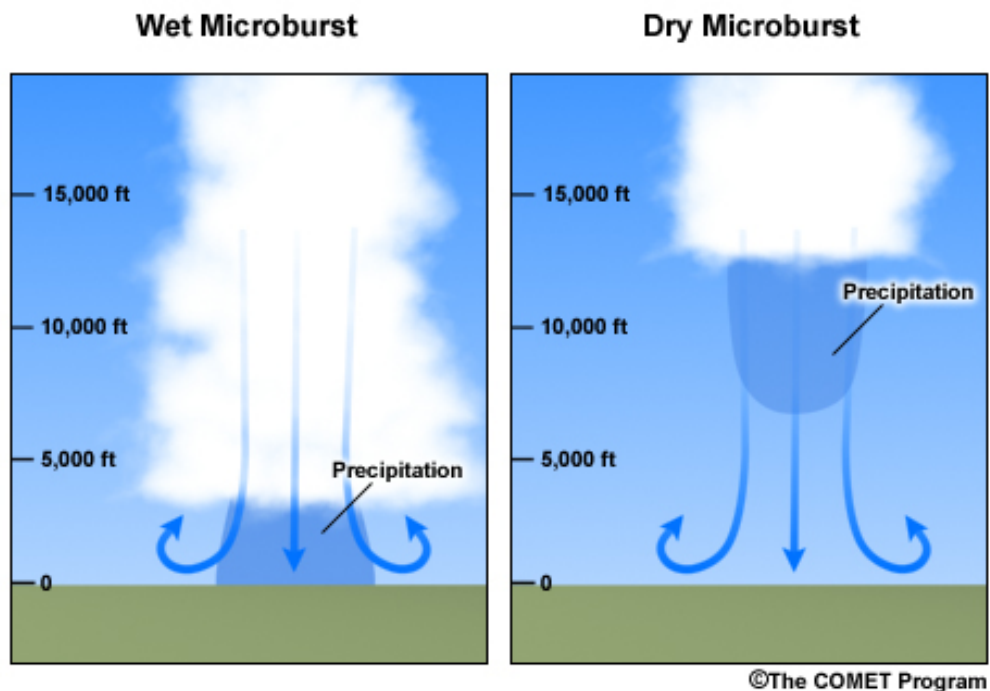- Often there is a "rain gush" coincident with the microburst.

Figure 12: Schematic of a dry and wet microburst. [Credit: COMET]

Detection of Microbursts

Figure 13: A dry (top) and wet (bottom) microburst. [Credit: NCAR/NOAA]

- Doppler radar (airport and aircraft)

    - best when precipitation is present
    - terminal doppler weather radar (TDWR)

- Low-level wind shear alert system (LLWAS)

    - a network of wind sensors positioned around the airport
    - does not detect elevated microbursts or microbursts that are between sensors

Aviation

Microbursts are extremely hazardous to low-flying aircraft because of

- low airspeed

- proximity to the ground

- "dirty" aerodynamic configuration (flaps out, gear down)

- difficulty of visual microburst detection
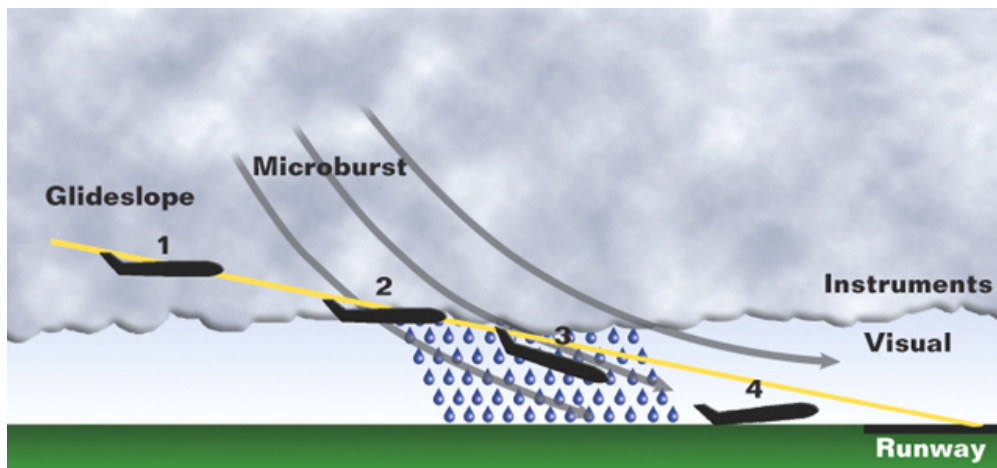
- rapid onset and short duration

Figure 14: Schematic showing how airplanes are affected by microbursts. [Credit: AOPA]

Through research, training, and observations, fatalities caused by wind shear associated with microbursts have been significantly reduced.
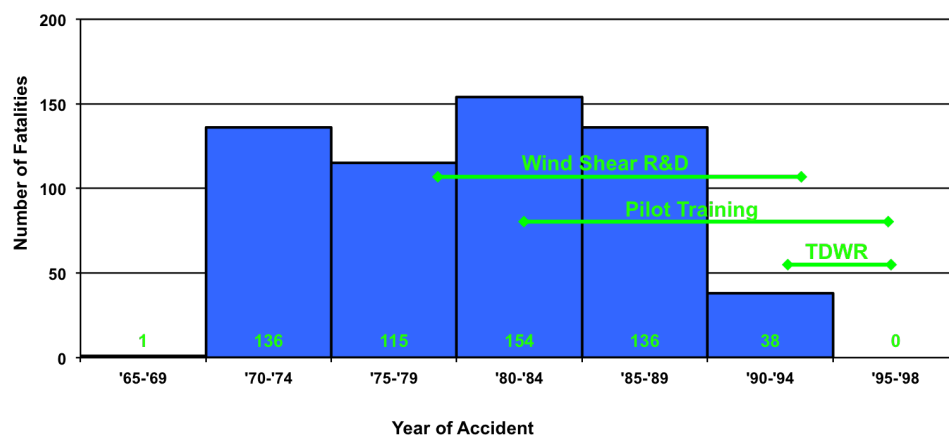

Figure 15: Fatalities associated with aviation wind shear accidents. [Credit: Dr. Kelvin Droegemeier]