Convective Dynamics

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Overview

Administrative
- Homework 2
- Exam 1

Convective Dynamics
- Introduction to Thunderstorms/Moist Atm. Convection
- Single-Cell Storms

Homework 2

Originally planned to assign on Mar 3, due Mar 24.

Now will be assigned on Mar 5, due Mar 26.

Exam 1

Stats

- Mean: 86.7%
- Mode: 86%
- Median: 87%
- Std. Dev: 7.7%

Exam 1

Thoughts and suggestions

- Generally everyone did well.
- If you didn't do as well as you'd hoped, don't stress, this was only 15% of your final grade. There is plenty of time to rebound.
- We will go over the solutions today.
- Don't look at it immediately (put those pitchforks down).
- Take a day, then go through and make sure you understand where you missed.
- If you have any questions, feel free to email me or drop by my office.

Finally ...

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.

Introduction to Thunderstorms / Moist Atmospheric Convection

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

Introduction to Thunderstorms / Moist Atmospheric Convection

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.

Introduction to Thunderstorms / Moist Atmospheric Convection

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.

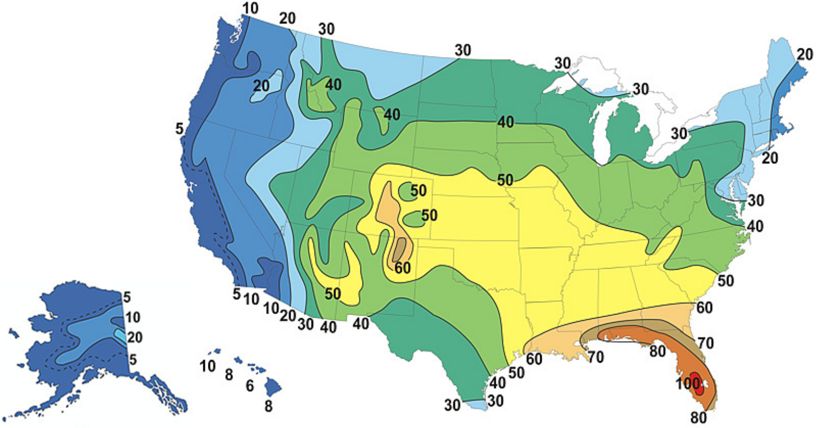

Figure: Average number of thunderstorm days each year throughout the U.S. [Credit: NWC]

Climatology

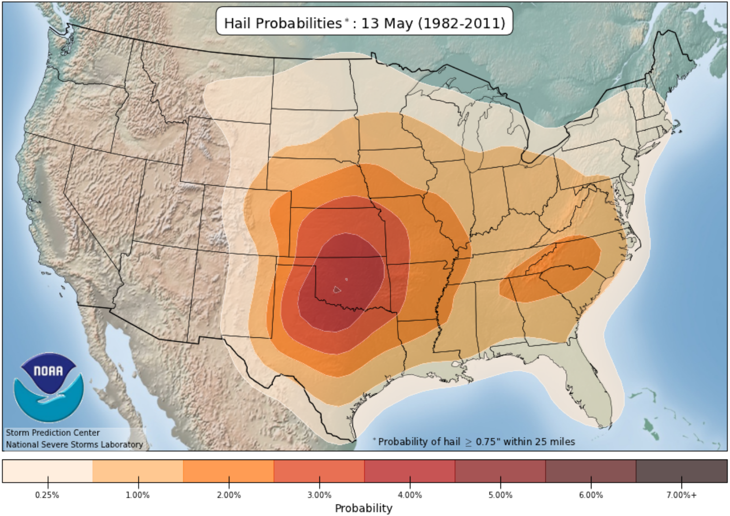

Figure: Climatological probabilities of several severe weather categories. [Credit: SPC]

Climatology

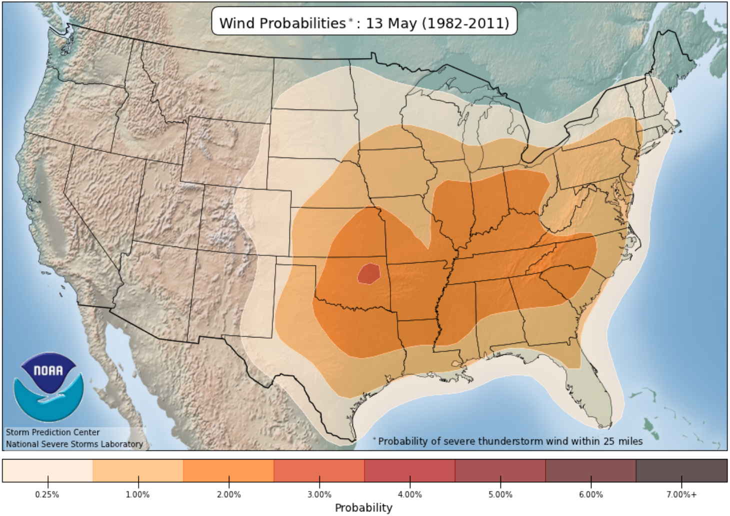

Figure: Climatological probabilities of several severe weather categories. [Credit: SPC]

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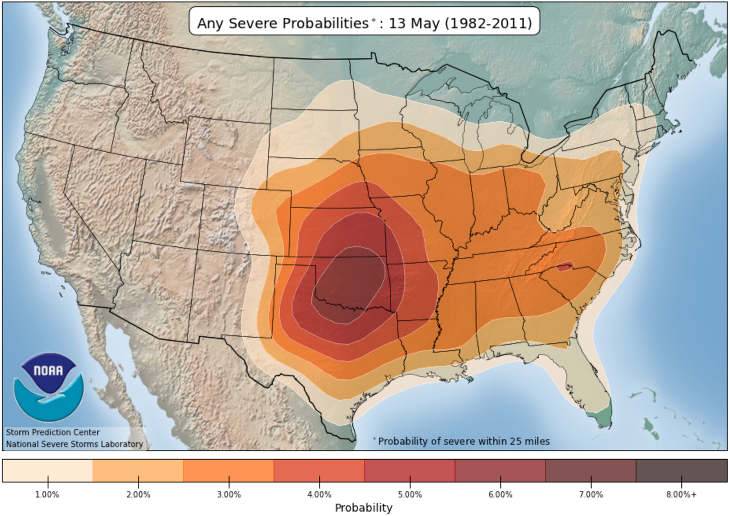

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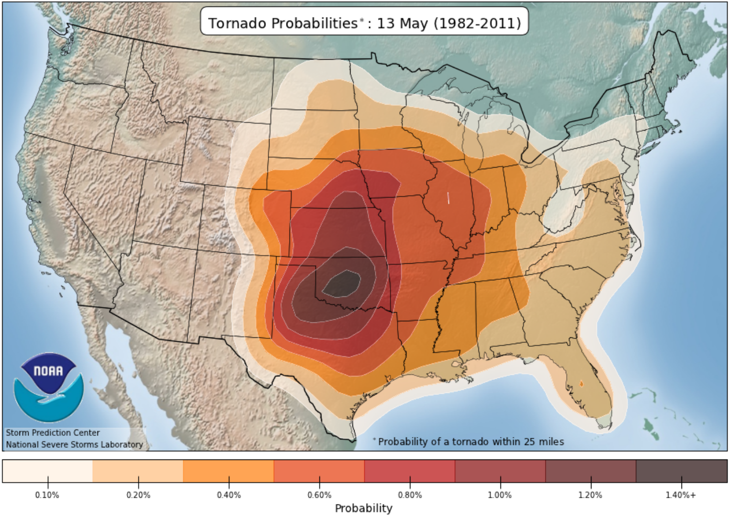


Figure: Climatological probabilities of several severe weather categories. [Credit: SPC]

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.

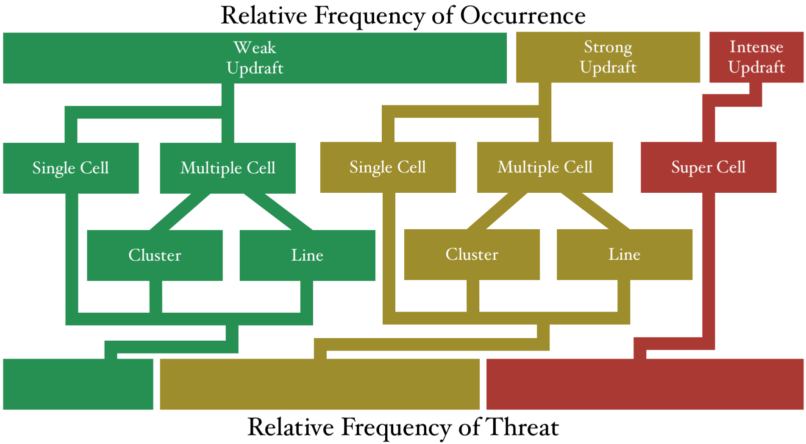
Modes of Convection / Storm Classification

- **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.

Modes of Convection / Storm Classification

- **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.

Thunderstorm Spectrum



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.

Basic Dynamics

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

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

where L is the combined liquid and ice water content.

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.

Convective Available Potential Temperature (CAPE)

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.

Convective Available Potential Temperature (CAPE)

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

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

.

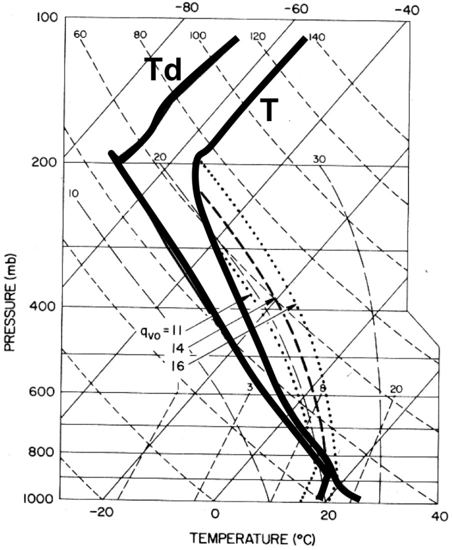
Convective Available Potential Temperature (CAPE)

CAPE is depicted on a Skew-T diagram as the positive area where the air parcel temperature is warmer than the environment (see upcoming figure).

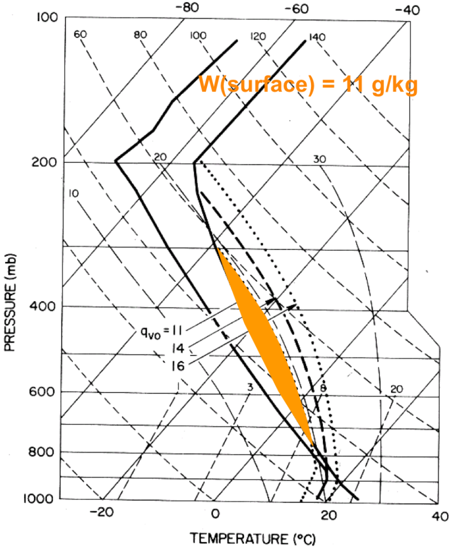
It may be increased by an increase in surface temperature, an increase in low-level moisture, or a cooling in the mid-levels of the atmosphere.

Consider, for example, an increase in low-level moisture.

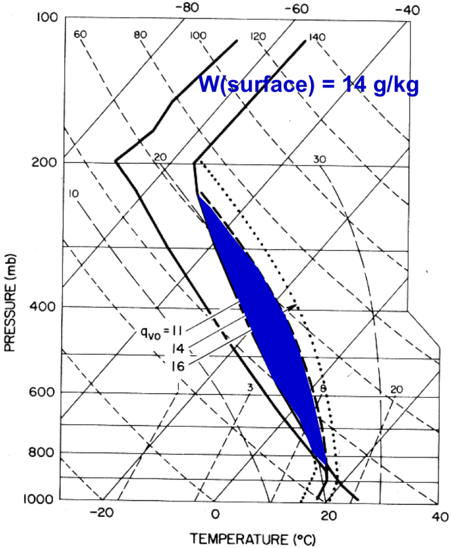
How Can CAPE Increase?



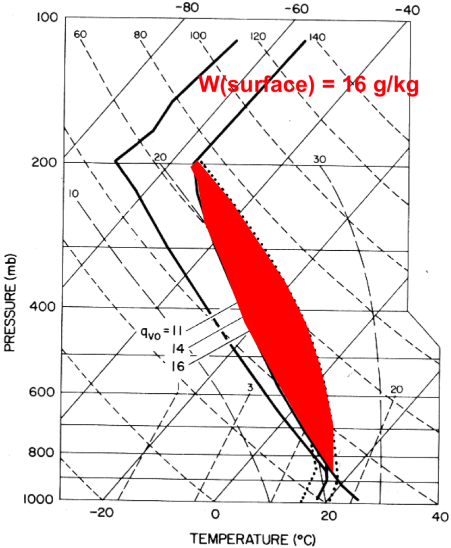
How Can CAPE Increase?



How Can CAPE Increase?



How Can CAPE Increase?



Other Physical Parameters

- **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

Other Physical Parameters

- **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).

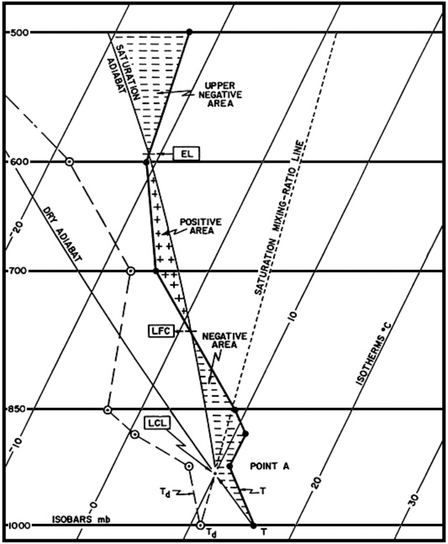
Parcel Theory

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.

Skew-T



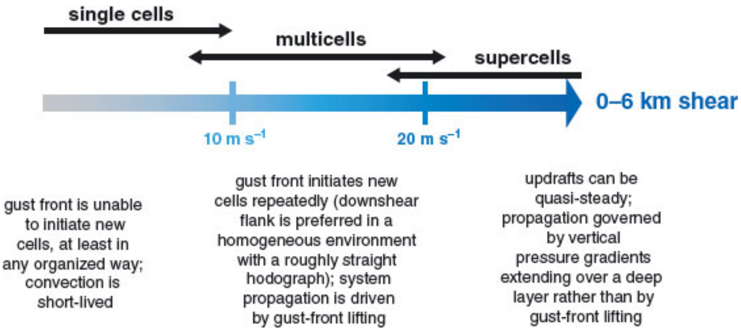
500
600
700
850
1000
SATURATION ADIABAT
UPPER NEGATIVE AREA
EL
POSITIVE AREA
LFC
NEGATIVE AREA
LCL
POINT A
DRY ADIABAT
SATURATION MIXING-RATIO LINE
ISOTHERMS °C
ISOBARS mb
-20
-10
0
10
20
30
T_d
T

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.

Vertical Wind Shear



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.

Predicting Thunderstorm Type

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

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

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).

Predicting Thunderstorm Type

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

Large values are associated with single-cell storms, while smaller values ($\sim$ 10-20) are associated with supercells.

Predicting Thunderstorm Type

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

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).

Single-Cell Storms

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 $< 1\ \mathrm{h}$, 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.

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

Life Cycle

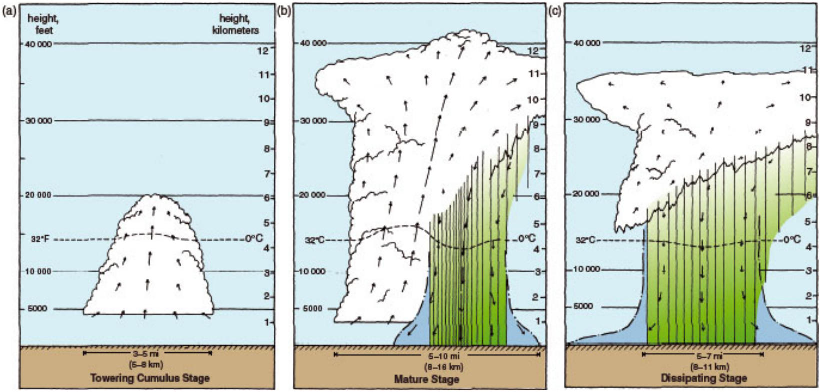
Mature Phase

- 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.

Life Cycle

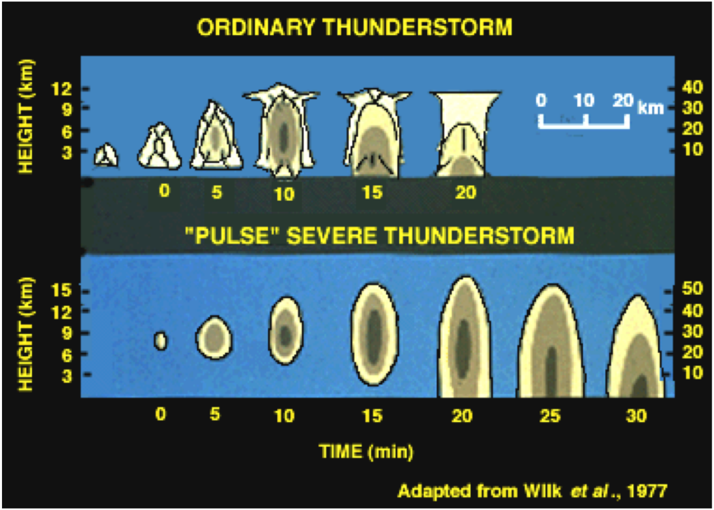
Dissipating Phase

- 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."


(a)
height, feet
height, kilometers
40 000
30 000
20 000
32°F
0°C
10 000
5000
3–5 mi
(5–8 km)
Towering Cumulus Stage
(b)
40 000
30 000
20 000
32°C
0°C
10 000
5000
5–10 mi
(8–16 km)
Mature Stage
(c)
40 000
30 000
20 000
32°C
0°C
10 000
5000
5–7 mi
(8–11 km)
Dissipating Stage

Life Cycle

Life Cycle



ORDINARY THUNDERSTORM
HEIGHT (km)
12
9
6
3
0
5
10
15
20
0 10 20 km
40
30
20
10
"PULSE" SEVERE THUNDERSTORM
HEIGHT (km)
15
12
9
6
3
0
5
10
15
20
25
30
50
40
30
20
10
TIME (min)
Adapted from Wilk et al., 1977

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 $(Ldq_v = c_p dT)$

Development and Decay of a Single-Cell Storm

- 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.

$$B = g(\theta' / \overline{\theta}) \qquad -gL$$

$$10 \times 3/300 \qquad -10 \times 0.01 \ \mathrm{kg/kg}$$

Therefore, 10 $\mathrm{g/kg}$ of cloud or rain water will offset a 3 K temperature surplus.

Development and Decay of a Single-Cell Storm

- 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.

Development and Decay of a Single-Cell Storm

- 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.

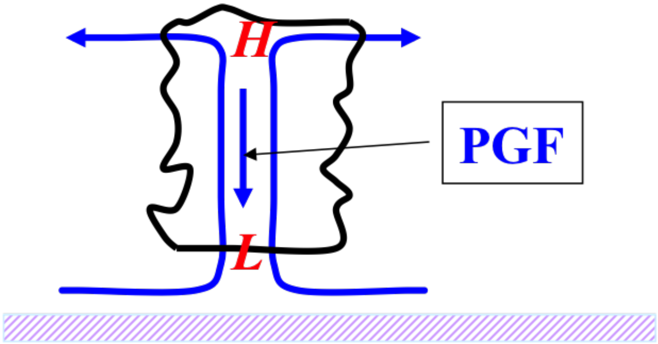
Entrainment

- 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.

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

Impact of the Pressure Gradient Force



Impact of the Pressure Gradient Force

- 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.

Impact of the Pressure Gradient Force

- 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

Impact of the Pressure Gradient Force

- 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.

Impact of the Pressure Gradient Force

- 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.

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

Downbursts and Microbursts

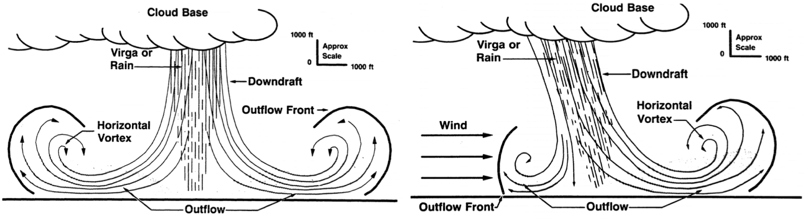


Figure: Diagram of a symmetric (left) and asymmetric (right) microburst. [Credit: FAA]

Downbursts and Microbursts

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).

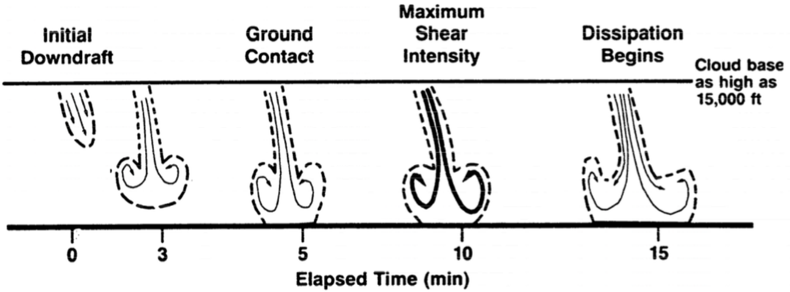


Figure: Evolution of a microburst. Winds typically intensify for about 5 min after ground contact and dissipate after 10-20 min. [Credit: FAA]

Downbursts and Microbursts

Dry Microburst

- 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.

Downbursts and Microbursts

Wet Microburst

- 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.

Downbursts and Microbursts

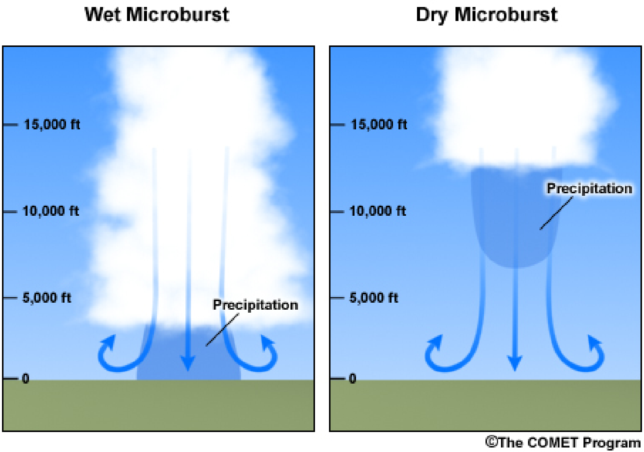


Figure: Schematic of a dry and wet microburst. [Credit: COMET]

Detection of Microbursts

Figure: A dry microburst. [Credit: NOAA]

Detection of Microbursts

Figure: A wet microburst. [Credit: NCAR]

Detection of Microbursts

- 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

Microbursts and Aviation

Microbursts are extremely hazardous to low-flying aircraft due to

- low airspeed
- proximity to the ground
- "dirty" aerodynamic configuration (flaps out, gear down)
- difficulty of visual microburst detection
- rapid onset and short duration

Microbursts and Aviation

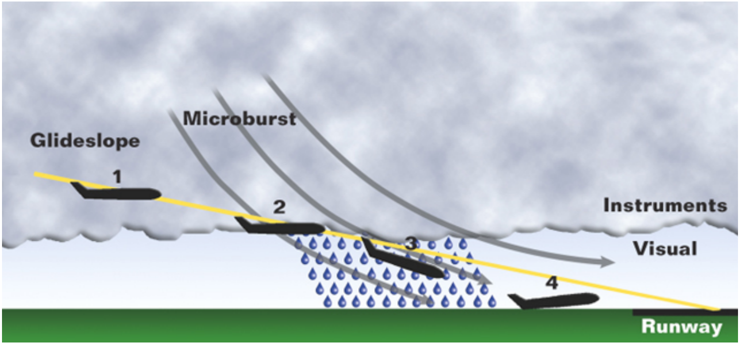


Figure: Schematic showing how airplanes are affected by microbursts. [Credit: AOPA]

Microbursts and Aviation

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

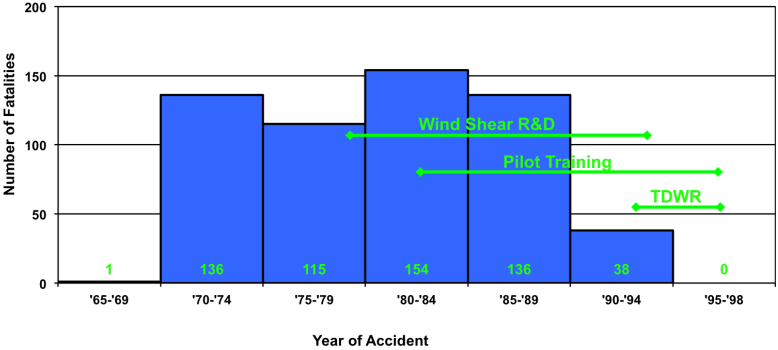


Figure: Fatalities associated with aviation wind shear accidents. [Adapted from Dr. Kelvin Droegemeier]

The End