Chapter 8 cont. – Clouds and Storms

Spring 2018
Clouds and Storms

• Clouds cover ~ 50% of earth at any time.

• Clouds are linked to a number of condensation processes.

• Cloud morphology, cloud types, associated processes, Storm types
Cloud Morphology

• Convective ascent from conditional instability
  \[ W \sim 1-10's \text{ m/s} \]
  \[ \geq 1 \text{ g/m}^3 \]
  Lifetime: minutes to hours
  Convective clouds

• Forced lifting by circulation
  \[ W \sim 0.1 \text{ m/s} \]
  \[ \leq 1 \text{ g/m}^3 \]
  Lifetime: hours – 10's of hours
  Layer clouds
Morphology continued

- Forced uplift by mountains, etc.
  - \( W \): variable
  - Few (1/10)'s g/m\(^3\)
  - Many hours in steady winds
  - Orographic clouds

- Saturated air in contact with cold surface.
  - Cooling by radiation or advection of warm air over cold surface.
  - Fog.
Morphology continued

- Contrails and sea-smoke
  Mixing of parcels @ different temperatures.

- Rapid adiabatic expansion due to local lowering of pressure.
  Funnel clouds/condensation funnel.
Types of clouds

• Rather complete classifications can be formed.
  - Cumulus: heap or pile => convective clouds
  - Stratus: layer
  - Cirrus: fibrous clouds
  - Nimbus: rain clouds
  - Etc......

• More important: Associate clouds with processes.
Fig. 5.1 This series of photographs shows the transformation process from cumulus congestus to cumulonimbus clouds during a period of 55 min. See text for discussion. (Photos from Y. Itoh and S. Ohta, "Cloud Atlas: An Artist's View of Living Cloud," Chijinshankan Co., Ltd., Tokyo, Japan, 1967.)
Convective elements

- Thermal (rising buoyant air) rises to LCL and above.
  - LCL: Lifting condensation level or level at which lifted air becomes saturated.
- Entrainment
  - Thermal turned inside out as rising motions push against overlying air.
  - Sweeps in environmental air and thermal expands.
  - Can dilute thermal and reduce the buoyancy.
- Tower: buoyant to the limit of upward buoyancy/momentum, then evaporation.
  - Tower rises to $\sim 1.5 \times$ diameter of thermal above the cloud base.
Convective formation

Fig. 5.2  A thermal at various stages in its development. The arrows indicate the air motions. (a) Below the lifting condensation level (LCL) the diameter of the (invisible) thermal increases as it rises. (b) Above the LCL the thermal becomes visible as a cloud tower. It ceases to widen because parts diluted by entrainment are left behind. (c) The cloud tower at its maximum height. Thereafter it becomes eroded, sinks, and evaporates. A cumulus cloud consists of a number of such thermals at various stages in their life history.
Convective elements cont.

- Cumulus cloud: many towers/thermals
- Deep convection: towers penetrate depth of troposphere.
- Rising motion balanced by compensating downward motion => downdraft
  - Mass balance.
  - Can occur inside or outside of cloud.
Convective Downdrafts

- Sub-saturated air with water drops.
  Sub-saturated by entrainment.
- Drops evaporate => temperature decreases.
  Negative buoyancy => sinking.
- Sinking parcel accumulates more liquid water and temperature increases (compression).
  More evaporation.
  More sinking.
- At extreme: Downburst
  convective instability (upside down)
Fig. 5.3  Measurements of (a) vertical air velocities and liquid water contents and (b) droplet size distributions, through the middle of a cumulus cloud about 2 km in depth. The positions where the three droplet size distributions shown in (b) were measured are indicated by 1, 2, and 3 in (a). [From J. Atmos. Sci. 26, 1053 (1969).]
Layer clouds

• Most typically form along warm and cold fronts.
• 1st: High, thin clouds
  Ice crystals, falling ice crystals (fall streaks or virga)
• 2nd: Cirrostratus – Diffuse
  Halo formation.
• 3rd: Lower clouds: altostratus
  ~ 2-3 km thick, sun obscured, corona.
• 4th: Thickest/lowest: nimbostratus
  Precipitation.
  May have ice and liquid layers.
Fig. 5.15  A vertical cross section illustrating the formation of mountain and lee waves and an associated mountain-wave cloud (over the mountain) and lee-wave clouds (downwind of the mountain).
More Orographic Clouds

Fig. 5.16  Average distribution of (a) liquid water (in grams per cubic meter) in clouds over the Cascade Mountains and (b) ice particle concentrations (per cubic centimeter), when the wind is blowing from left to right. [From J. Appl. Meteor. 14, 783 (1975).]
Lenticular Cloud
Air Mass Thunderstorm

- Isolated Feature (not associated with synoptic scale disturbances).

- Consist of several cells that grow and decay in succession.
  
  Each have a lifetime of about $\frac{1}{2}$ hour.

- Three stages
  
  Cumulus, mature, dissipating
Airmass Thunderstorm
Cumulus Stage

- Buoyant plume

- Updraft velocity increases rapidly with height.
  
  Top has $w \sim 10 \text{ m/s}$.
  Supercooled drops may be present well above freezing level.

  Hazard for aircraft.
Mature Stage

- Vigorous downdraft circulation
  - Initiated by downward frictional drag force.
  - Heaviest rain.
- Dry entrainment and evaporation of precipitation enhance downdraft.
- Max. W in middle of cloud.
- Detrainment at upper-levels
Dissipating Stage

- Downdraft becomes more extensive until it occupies virtually the entire cloud.
- No updraft of moist air, no condensation for positive buoyancy.
- Cloud drops can no longer grow.
- Shuts itself off, precipitation stops and the cloud evaporates.
Airmass Summary

• ~20% of water vapor condensed in the updraft region actually reaches the ground.
  Rest evaporates in cloud.
  Updraft often is left behind as cloud debris.

• Summary
  Short lived (Why?).
  Rarely produces destructive winds or hail.
Severe storms

- Longer lasting, stronger
- Generally, more organized
  - Less destructive interference with updrafts.
- Vertical shear of horizontal wind
- Mesoscale organization (10's-100's km) [MCS]
- Squall lines, multi-cell storm, super-cell storm, MCC's (Mesoscale convective complex).
Squall line

(a) Temperature profile
(b) Wind speed profile
(c) Cross-section of squall line with labels:
- Storm motion
- "Overshooting" cloud top
- Tropopause
- Anvil
- Mamma
- New cells
- Inversion
- Moist layer
- Gust front
Squall Lines

- “Line Thunderstorms” usually accompanied by gusty surface winds, hence the name.

- Key points:

  Note shear: Upper air Overtakes environmental air.

  At low levels, arrows represent environmental air (pre-storm environment) being overtaken by the squall line.

  Weak inversion keeps warm moist air trapped for feeding into line.

  Cold air from downdraft streams out ahead (outflow or gust front), lifts warm moist air to LCL, then LFC, buoyantly rises to tropopause.
Keys cont.

- Overtaking air from behind
  
  Relatively dry.
  
  Precipitation falling in it evaporates.
  
  Air cools to $T_w$ and sinks due to cooling.
  
  Downdraft is strengthened.

- Complimentary behavior

  Lifted air produces precipitation and initiates downdraft.
  
  Downdraft advances to surface lifting warm moist air.
  
  Need slope so precipitation can fall on cool air.
  
  Vertical shear provides this and does the organizing.
Advanced dynamics of Squall Lines

- Transport high quantities of high $\theta_e$ air upward.

- Replaces it with low $\theta_e$ air.

- Eliminate or reduce the $\theta_e$ gradient.

- Eliminate or reduce convective instability.
Squall line
Squall line Addendum

- Any line of continuous or nearly continuous convective cells.
- Large length to width ratio.
- May be composed of ordinary cells and/or supercells depending on environment.
- Supercells may exist through the entire line, but they don't last long
  Storm motions disrupts other cells.
  Cells at ends of lines are longer lived.
  Usually found at southern edge or along breaks.
Multi-cell storms/Right Moving

- Some degree of mesoscale organization present.
  Individual cells can still be identified.

- Right Moving multi-cell storm
  Thunderstorm movement directed toward the right of environmental air flow in the middle troposphere.
  Clockwise turning of environmental wind with height (vertical shear of horizontal wind).
Right moving multi-cell storm

Fig. 5.24  Schematic illustration of right-moving multicell storm. (a) Vectors showing lower tropospheric ($V_L$) and midtropospheric ($V_M$) winds relative to the ground. (b) Positions of individual (lettered) cells at three successive times about 15 min apart. Note the development of new cell G and the dissipation of cells A and B.
Right Moving Multicell

- Movement of cells closely related to mid-tropospheric wind vector, $V_m$
  - Cells are lined up perpendicular to $V_m$.
  - Movement is parallel to $V_m$.
- Lower level wind feeds warm, moist air from south (e.g., Gulf of Mexico).
  - Low level flow feeds moisture to southern flank leading to preferential growth.
- Cells on north decay as they are cut-off from low-level flow.
- Cells move with $V_m$, but pattern shifts to right of $V_m$. 
Right Moving Multicell - Summary

- Combination of continuous generation of new cells on the right flank and dissipation of old cells on the left flank results in an effective propagation toward the right of $V_m$. 
Supercell

- Mesoscale organization.
- Whole cell behaves as a single entity, rather than a group of cells.
- Account for most tornadoes and damaging hail
- Doswell: “...a convective storm that possesses a deep, persistent mesocyclone”
  
  Deep: circulation is connected through a significant portion of the storm.
  
  Persistent: long compared to time parcel takes to go from cloud base to updraft top (10-20 minutes).
Supercell

Fig. 5.27a,b  Structure of a supercell storm (a) as seen from above and (b) as seen in a vertical cross section looking downstream in the direction of the midtropospheric winds. Areas of heavy stippling correspond to radar echoes; lighter stippling denotes clouds composed of small (non-reflective) cloud droplets. Arrows show projections of air motions in the updraft relative to the storm. Note that the arrows in (a) represent motion of air entering the storm at low levels and leaving at high levels, and that in (b) there is a component of air motion perpendicular to the page. [Adapted from Quart. J. Roy. Met. Soc. 102, 499 (1976).]
Supercell characteristics

• Forward flank downdraft (FFD): downdraft associated evaporative cooling and drag from precipitation.

• Rear flank downdraft (RFD): downdraft associated with mid-level air approaching the storm from “behind” storm.

  Clouds and precipitation particles on the rear flank mix with dry mid-level air, evaporate, and create downdraft.
Supercell characteristics cont.

- **Rain free base**
  
  Cloud particles are very small and are carried aloft by the strong updrafts.

  Middle and upper troposphere winds carry particles downwind so precipitation rarely appears in the core of the updraft region.

- **Echo free vault or vault (weak echo region)**

  Particles are so small that they produce only weak echoes.

  Large number of particles: very dark region.

  BWER – Bounded Weak Echo Region
radar detected rain and hail

FFD = Forward Flank Downdraft
RFD = Rear Flank Downdraft
OD = Occlusion Downdraft
UD = Updraft

warm, moist air
rear flank gust front
forward flank gust front
Courtesy of the American Meteorological Society
Supercell Types

• Classic

• Low Precipitation (LP)
  “Barbershop pole” appearance of updraft
  Minimum output of precipitation
  Tornadoes rather easy to spot

• High Precipitation (HP)
  Copious rainfall
  Rain tends to obscure tornadoes
Downdrafts/Microbursts

- evaporating rain consumes latent heat
- cooler, more dense air sinks
- precipitation drag

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Downdrafts/Microbursts

(A) Weak Winds
   calm

(D) Strong Winds

(B) Strong Winds

(E) Strong Winds
   strong background winds
   strongest outflow

(C) Stagnation cone

(F) Stagnation cone

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Microbursts Hazards

A
TAKEOFF

B
LANDING

Glide Slope

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Courtesy of the Theodore Fujita Family

Crosswind Burst
Headwind Burst
Tailwind Burst
Crosswind Burst
Drift Left
Airspeed Increase
Airspeed Decrease
Hail Formation

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Hail Formation

- Cloud drops are carried high into storms and freeze.
  
  Form ice crystals
- Some crystals get carried away downwind and help form anvil downwind.
- Some fall on upwind side of updraft core.
- Ice crystals are swept back into updraft in region of supercooled drops.
  
  Rimming takes place and hail forms
- Size of hail depends on how long it stays in updraft.
  
  For rotating storms, hail can circle updraft and get very, very large.
Hail Formation (Large)