Stability and Cloud Development

AT350

Why did this cloud form, whereas the sky was clear 4 hours ago?

Stability in the atmosphere

An Initial Perturbation
Stable
Unstable
Neutral

If an air parcel is displaced from its original height it can:
Return to its original height - Stable
Keep right on moving because it is buoyant - Unstable
Stay at the place to which it was displaced - Neutral

the concept of stability
Buoyancy

- An air parcel rises in the atmosphere when it’s density is less than its surroundings.
- Let $\rho_{\text{env}}$ be the density of the environment. From the Equation of State/Ideal Gas Law:
  \[ \rho_{\text{env}} = \frac{P}{RT_{\text{env}}} \]
- Let $\rho_{\text{parcel}}$ be the density of an air parcel. Then:
  \[ \rho_{\text{parcel}} = \frac{P}{RT_{\text{parcel}}} \]
- Since both the parcel and the environment at the same height are at the same pressure:
  - When $T_{\text{parcel}} < T_{\text{env}}$, $\rho_{\text{parcel}} > \rho_{\text{env}}$
  - When $T_{\text{parcel}} > T_{\text{env}}$, $\rho_{\text{parcel}} < \rho_{\text{env}}$

What is the lapse rate?

- The lapse rate is the change of temperature as a function of altitude.
- There are two kinds of lapse rates:
  - Environmental Lapse Rate
    - What you would measure with a weather balloon
  - Parcel Lapse Rate
    - The change of temperature that an air parcel would experience when it is displaced vertically
    - This is assumed to be an adiabatic process (i.e., no heat exchange occurs across parcel boundary).

Stability and the dry adiabatic lapse rate

- Atmospheric stability depends on the environmental lapse rate:
  - A rising unsaturated air parcel cools according to the dry adiabatic lapse rate.
  - If this air parcel is
    - warmer than surrounding air it is less dense and buoyancy accelerates the parcel upward
    - colder than surrounding air it is more dense and buoyancy forces oppose the rising motion

Parcel lapse rate...

The atmospheric dry adiabatic lapse rate is ~5.4°F/1000 ft or 10°C/1000 m.

The actual, environmental lapse rate may be greater or smaller than this.
A saturated rising air parcel cools less than an unsaturated parcel

- If a rising air parcel becomes saturated condensation occurs
- Condensation warms the air parcel due to the release of latent heat
- So, a rising parcel cools less if it is saturated
- Define a moist adiabatic lapse rate
  - ~ 6°C/1000 m
  - Not constant (varies from ~ 3-9°C)
  - depends on T and P

Stability and the moist adiabatic lapse rate

- Atmospheric stability depends on the environmental lapse rate
  - A rising saturated air parcel cools according to the moist adiabatic lapse rate
  - When the environmental lapse rate is smaller than the moist adiabatic lapse rate, the atmosphere is termed absolutely stable
    - Recall that the dry adiabatic lapse rate is larger than the moist
    - What types of clouds do you expect to form if saturated air is forced to rise in an absolutely stable atmosphere?

What conditions contribute to a stable atmosphere?

- Radiative cooling of surface at night
- Advection of cold air near the surface
- Air moving over a cold surface (e.g., snow)
- Adiabatic compression due to subsidence (sinking)

Absolute instability

- The atmosphere is absolutely unstable if the environmental lapse rate exceeds the moist and dry adiabatic lapse rates
- This situation is not long-lived
  - Usually results from surface heating and is confined to a shallow layer near the surface
  - Vertical mixing can eliminate it
**Conditionally unstable air**

- What if the environmental lapse rate falls between the moist and dry adiabatic lapse rates?
  - The atmosphere is unstable for saturated air parcels but stable for unsaturated air parcels
  - This situation is termed *conditionally unstable*

- This is the typical situation in the atmosphere

---

**What conditions enhance atmospheric instability?**

- Cooling of air aloft
  - Cold advection aloft
  - Radiative cooling of air/clouds aloft
- Warming of surface air
  - Solar heating of ground
  - Warm advection near surface
  - Air moving over a warm surface (e.g., a warm body of water)
    - Contributes to lake effect snow
- Lifting of an air layer and associated vertical “stretching”
  - Especially if bottom of layer is moist and top is dry

---

**Cloud development**

- Clouds form as air rises, expands and cools
- Most clouds form by
  - Surface heating and free convection
  - Lifting of air over topography
  - Widespread air lifting due to surface convergence
  - Lifting along weather fronts
Fair weather cumulus cloud development

- Air rises due to surface heating
- RH rises as rising parcel cools
- Cloud forms at RH ~ 100%
- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion associated with high pressure system
- Sinking air is found between cloud elements
  - Why?

What conditions support taller cumulus development?

- A less stable atmospheric profile permits greater vertical motion

Determining Convective Cloud Bases

- Dry air parcels cool at the dry adiabatic rate (about 10 °C/km)
- Dew point decreases at a rate of ~ 2 °C/km
- This means that the dew point approaches the air parcel temperature at a rate of about 8°C/km
- If the dew point depression were 8°C at the surface, a cloud base would appear at a height of 1000 meters; 4 C at 500 meters etc.
  - Cloud base occurs when dew point = temp (100% RH)
- Each one degree difference between the surface temperature and the dew point will produce an increase in the elevation of cloud base of 125 meters
Determining convective cloud top

- Cloud top will be defined by the upper boundary of air parcel rising motion
- The area between the dry/moist adiabatic lapse rate, showing an air parcel’s temperature during ascent, and the environmental lapse rate, can be divided into two parts
  - A positive acceleration part where the parcel is warmer than the environment
  - A negative acceleration part where the parcel is colder than the environment
- The approximate cloud top height will be that altitude where the negative acceleration area becomes nominally equal to the positive acceleration area

Orographic clouds

- Forced lifting along a topographic barrier causes air parcel expansion and cooling
- Clouds and precipitation often develop on upwind side of obstacle
- Air dries further during descent on downwind side

some examples of clouds in stable and unstable layers