Cloud Development and Precipitation-I

GEOL 1350: Introduction To Meteorology

Stability and Cloud Formation

1. **Definitions and causes of stable and unstable atmosphere**

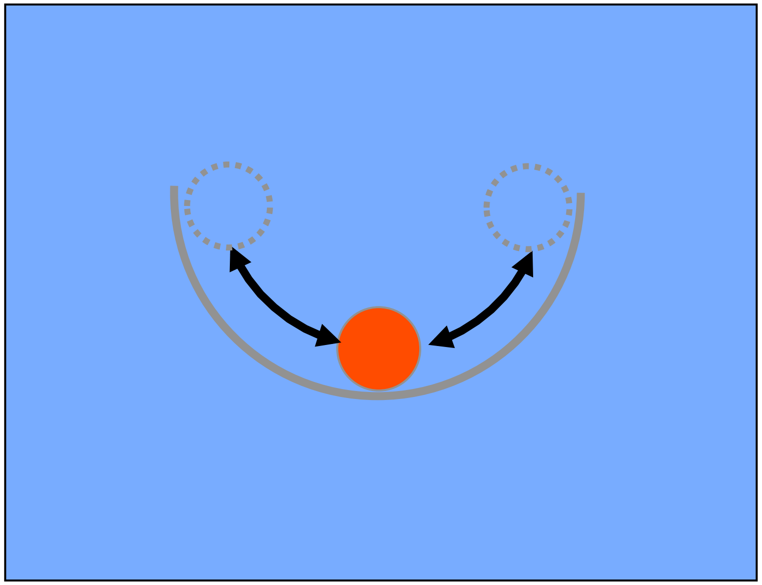
2. **Processes that cause instability and cloud development**

Stability of Atmosphere

- The ability of the air to return to its origin after displacement
- Depends on the thermal structure of the atmosphere
- Classified into three categories
  - Stable
  - Neutral
  - Unstable

Stable

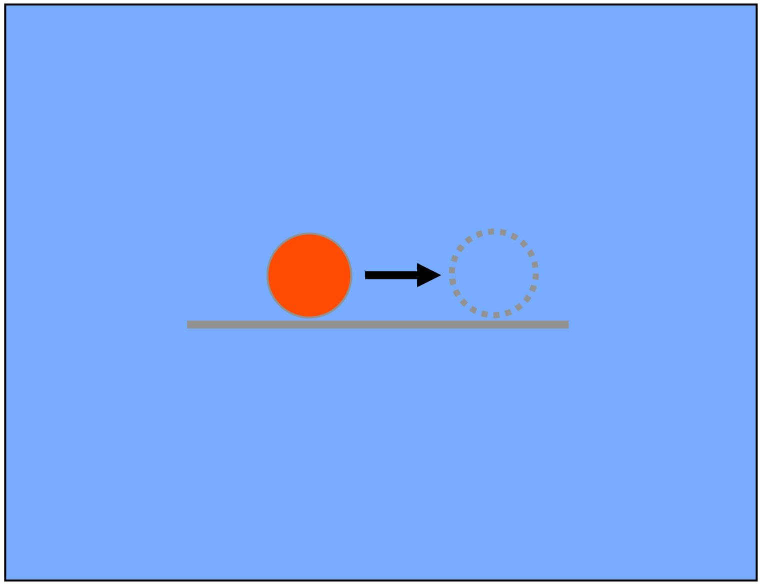
- Returns to original position after displacement



(courtesy F. Remer)

Neutral

- Remains in new position after being displaced



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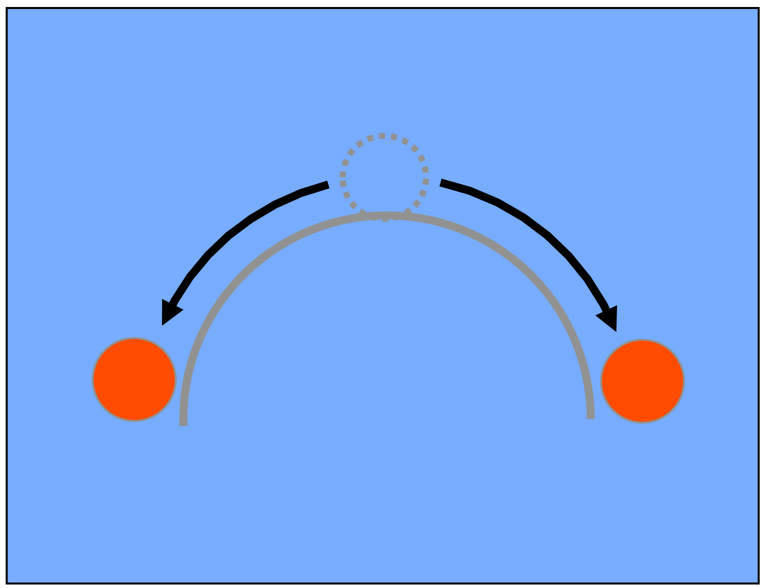
Unstable

- Moves farther away from its original position



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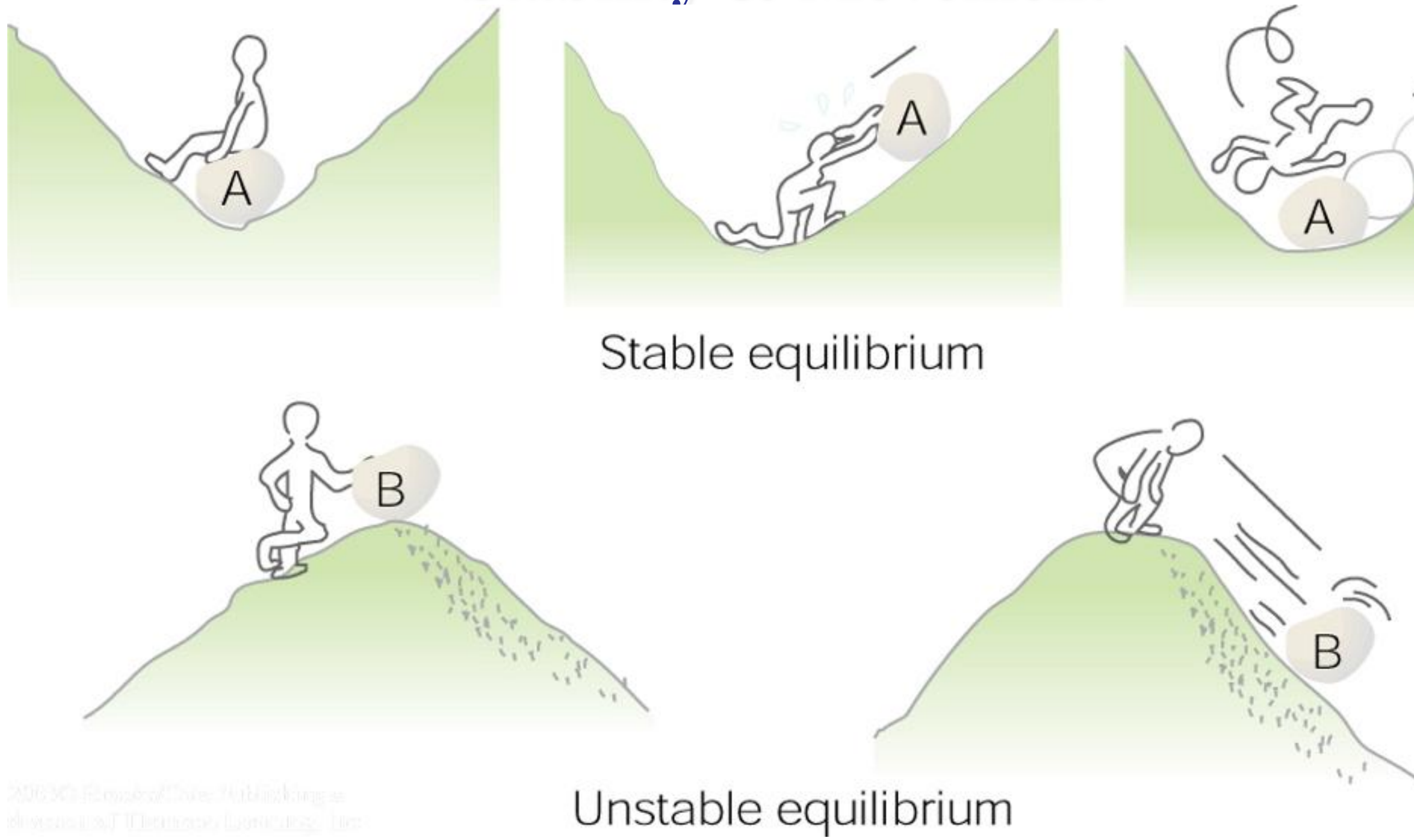
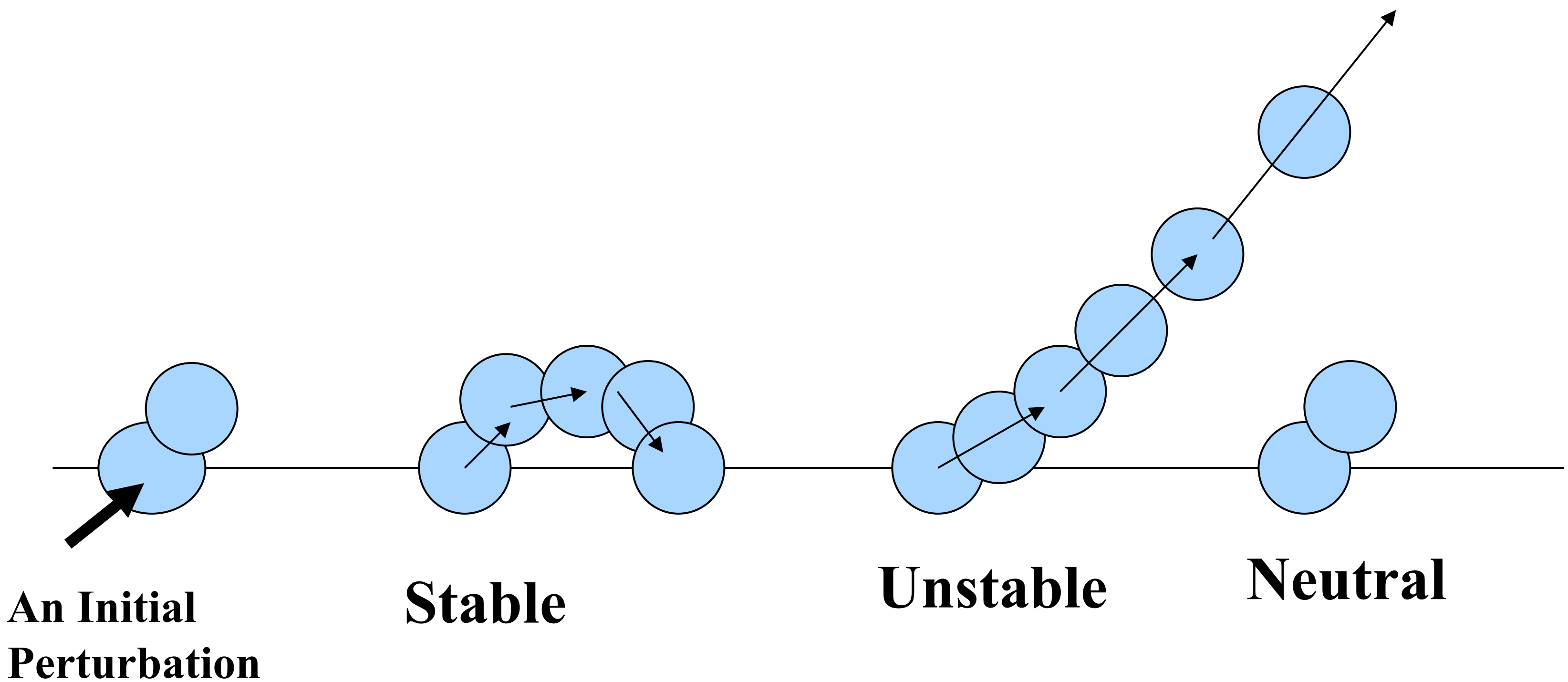
Stability & Movement



A rock, like a parcel of air, that is in stable equilibrium will return to its original position when pushed.

If the rock instead departs in the direction of the push, it was in unstable equilibrium.

Stability in the atmosphere



If an air parcel is displaced from its original height it can:

Return to its original height - Stable

Accelerate upward because it is buoyant - Unstable

Stay at the place to which it was displaced - Neutral

Stability of air parcel under the given environment

- A property of the **environment**
- ***Stable*** - displacement results in return to initial condition
- ***Unstable*** - displacement results in further displacement from initial condition

Stability is important because

- **Stability strongly influence vertical motion in the atmosphere**
- **Without vertical motion there would be no clouds, no precipitation, no storms - weather as we know it would simply not exist.**

There are two types of vertical motion:

- **forced motion** such as forcing air up over a hill, over colder air, or from horizontal convergence
- **buoyant motion** (convection) in which the air rises because it is less dense than its surroundings - *stability* is especially important here

Buoyancy

- **An air parcel rises in the atmosphere when it's density is less than its surroundings**
- **Since density is not measured directly, we need to convert this criterion to something easy to measure.**
- **Let ρ_{env} be the density of the environment. From the**

  Equation of State ($P=\rho_d R_d T$): $\rho_{env} = P/R_d T_{env}$
- **Let ρ_{parcel} be the density of an "dry" air parcel. Then**

  $\rho_{parcel} = P/R_d T_{parcel}$

- **Since both the parcel and the environment at the same height are at the same pressure**
  - **when $T_{parcel} > T_{env}$ $\rho_{parcel} < \rho_{env}$ (positive buoyancy)**
  - **when $T_{parcel} < T_{env}$ $\rho_{parcel} > \rho_{env}$ (negative buoyancy)♪**

Stability is determined by comparing parcel's temperature with that of its environment

Simply speaking,

$T_{parcel} > T_{env}$ **unstable**

$T_{parcel} < T_{env}$ **stable**

$T_{parcel} = T_{env}$ **neutral**

Lapse Rate

- The rate of temperature decrease with height is known as *lapse rate,* ($\Gamma = -\Delta T / \Delta z$)
- **There are two kinds of lapse rates:**
  - **Environmental Lapse Rate**
    - **What you would measure with a weather balloon; rate at which the surrounding air temperature decreases as we climb up.**
  - **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)**

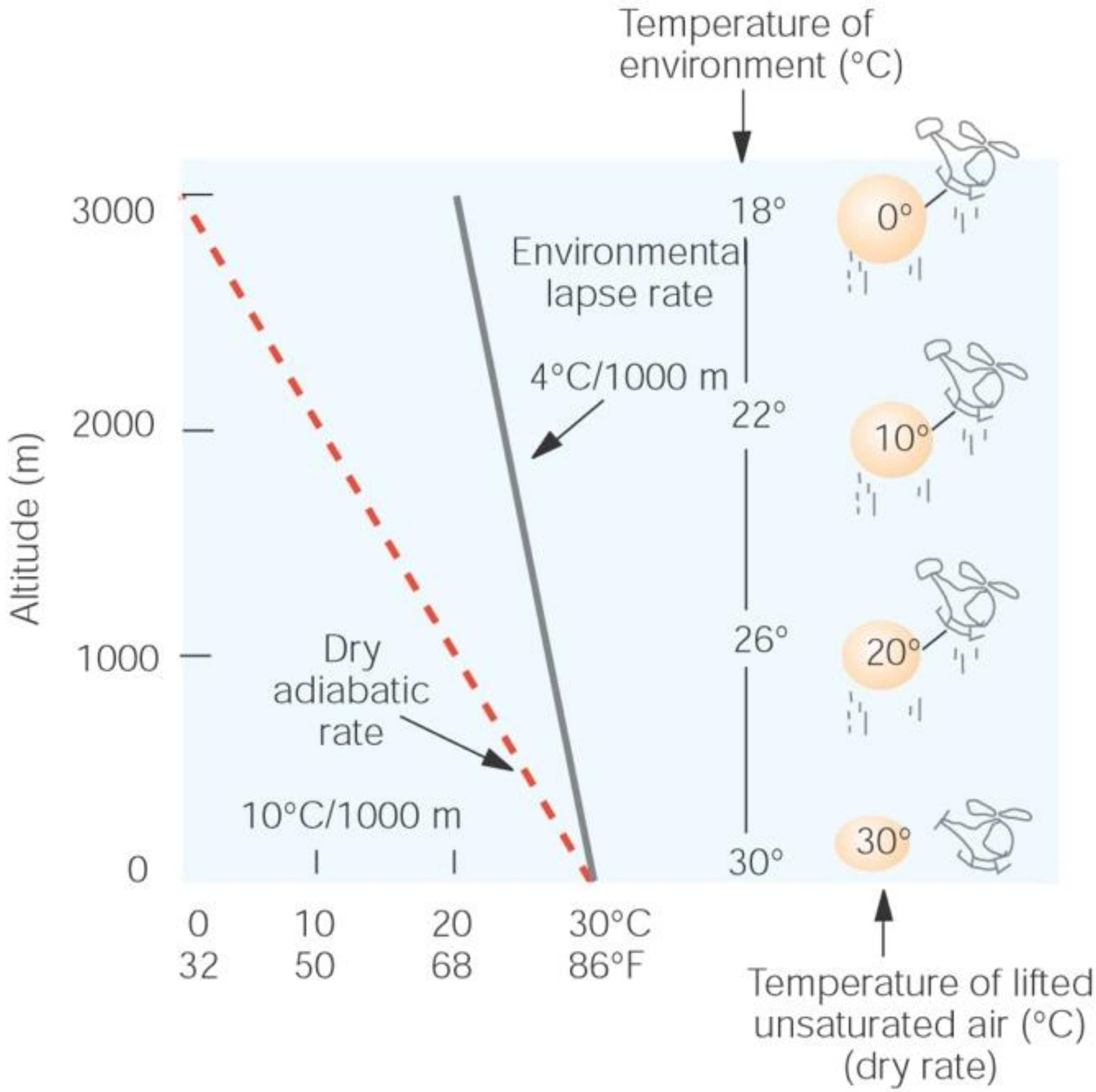
Dry adiabatic lapse rate – the rate of temperature decrease of a rising ***unsaturated*** air parcel

$$\Gamma_d = -\Delta T / \Delta z = 9.8\ ^{o}C\ km^{-1} \approx 10\ ^{o}C\ km^{-1}$$

Lifting a dry parcel

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**



Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position.

Dry Adiabatic Lapse Rate and Stability

A parcel of rising dry air cools at approximately 10° C/km

Because the environmental air cools more slowly, the parcel of air held by the helicopter is always cooler and sinks back to its original position.

Lifting a moist 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 saturated parcel cools less than unsaturated air parcel**
- **The cooling rate for a lifted saturated air parcel is called moist adiabatic lapse rate**

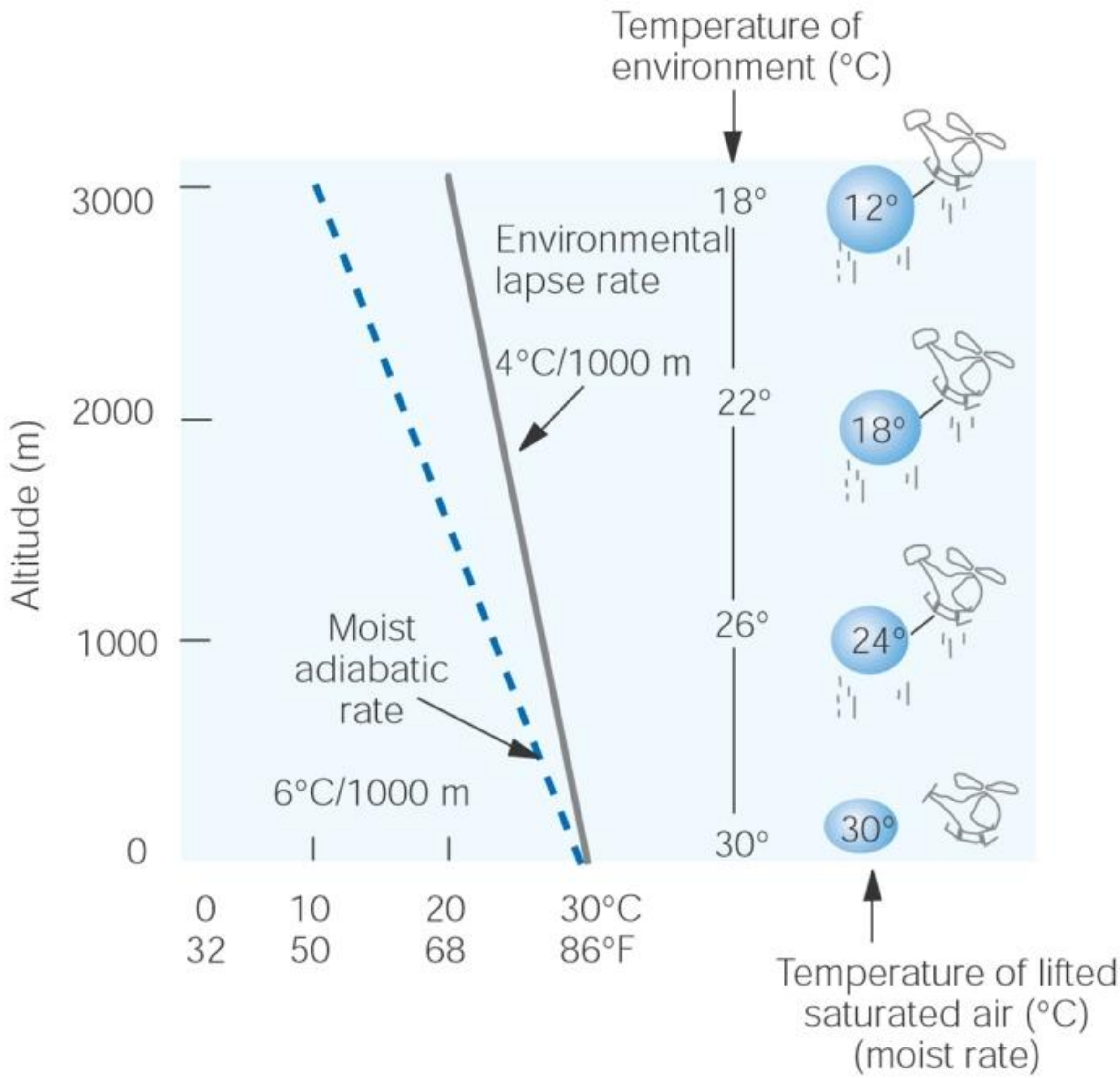
Moist adiabatic lapse rate

Decrease of temperature with height for saturated air

Near ground under humid condition, $\Gamma_s = 4\ ^oC$ / km

In lower to mid troposphere, $\Gamma_s = 6 - 7\ ^oC$ / km

Γ_s always $<$ Γ_d



Lifted, saturated air at each position is colder and heavier than the air surrounding it. If released, the parcel would return to its original position.

Moist adiabatic lapse rate and stability

–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 adiabatic lapse rate, so when the environmental lapse rate is less than the moist adiabatic lapse rate, it also smaller than the dry adiabatic lapse rate

The atmosphere is absolutely stable when the environmental lapse rate is less than the moist adiabatic lapse rate, $\Gamma < \Gamma_s$

What conditions makes atmosphere stable?

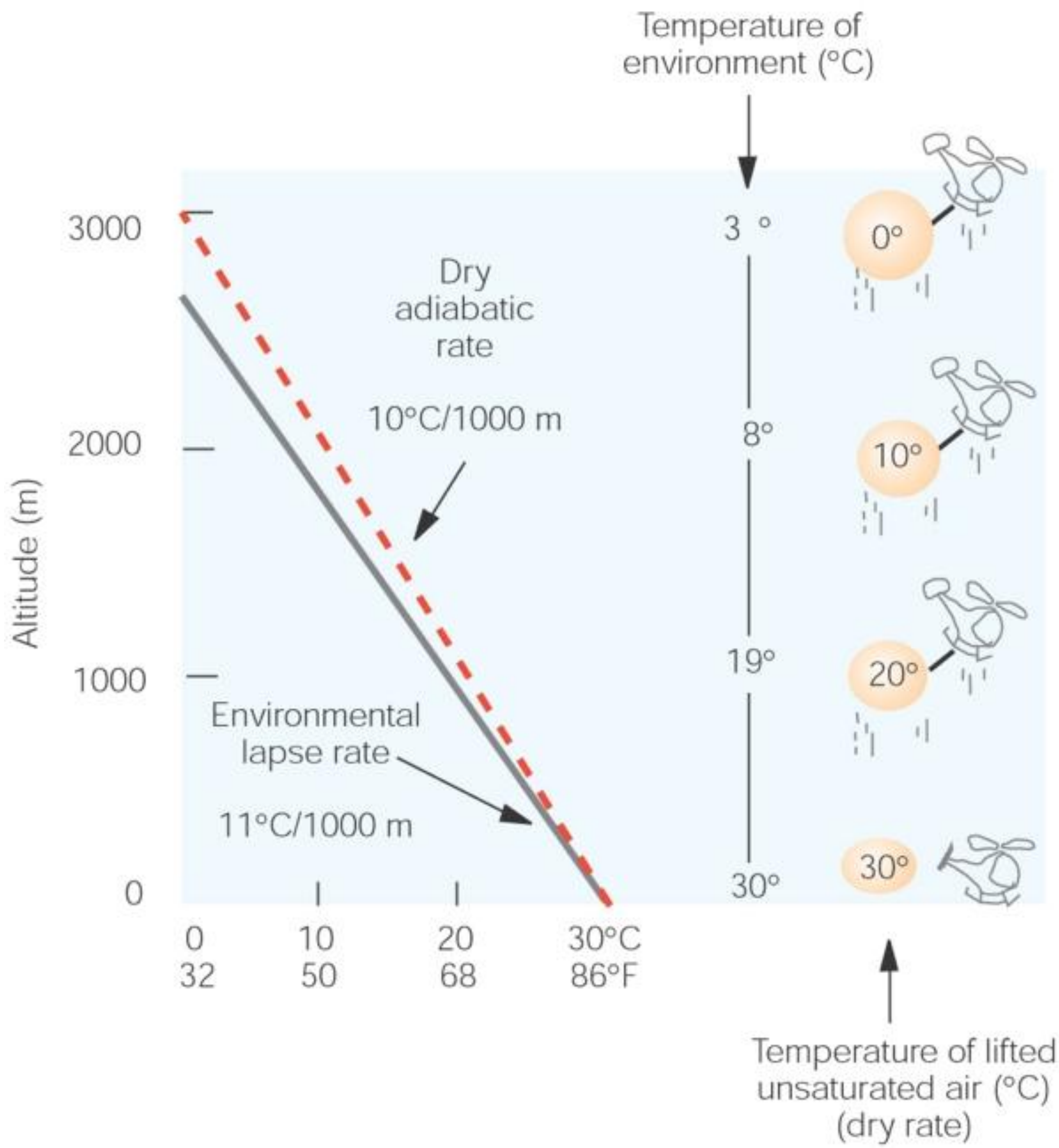
Warming aloft and cooling below

Air aloft may be warmed by

warm air advection and subsidence warming

Air near surface may be cooled by

- **Nighttime radiational cooling**
- **Cold air advection**
- **Air moving over a cold surface**



The rising, unsaturated air parcel at each level is warmer and lighter than the air around it. If given the chance, the air parcel would accelerate away from its original position.

Absolutely Unstable Atmosphere

Absolutely unstable conditions indicate that a lifted parcel of air, whether dry or moist, will be warmer than the surrounding environmental air, and hence continue to rise.

Absolute instability

- The atmosphere is **absolutely unstable** if the environmental lapse rate **exceeds** the dry adiabatic lapse rates $\Gamma > \Gamma_d$

- This situation is **usually short-lived**
  - Usually results from surface heating and is confined to a shallow layer near the surface

  - Vertical mixing can eliminate it

What makes atmosphere unstable?

Cooling aloft and warming below

The cooling of air aloft may be due to

- Cold air advection
- Cloud radiational cooling

The warming of the surface air may be due to

- Solar heating
- Warming air advection
- Air moving over a warm surface (e.g., warm body of water, contributing to the lake effect of snow

Heat as Instability Trigger

As the environmental lapse rate steepens, it becomes more unstable.

Heating air below, through contact with a hot surface or fire, will cause the environmental lapse rate to steepen.

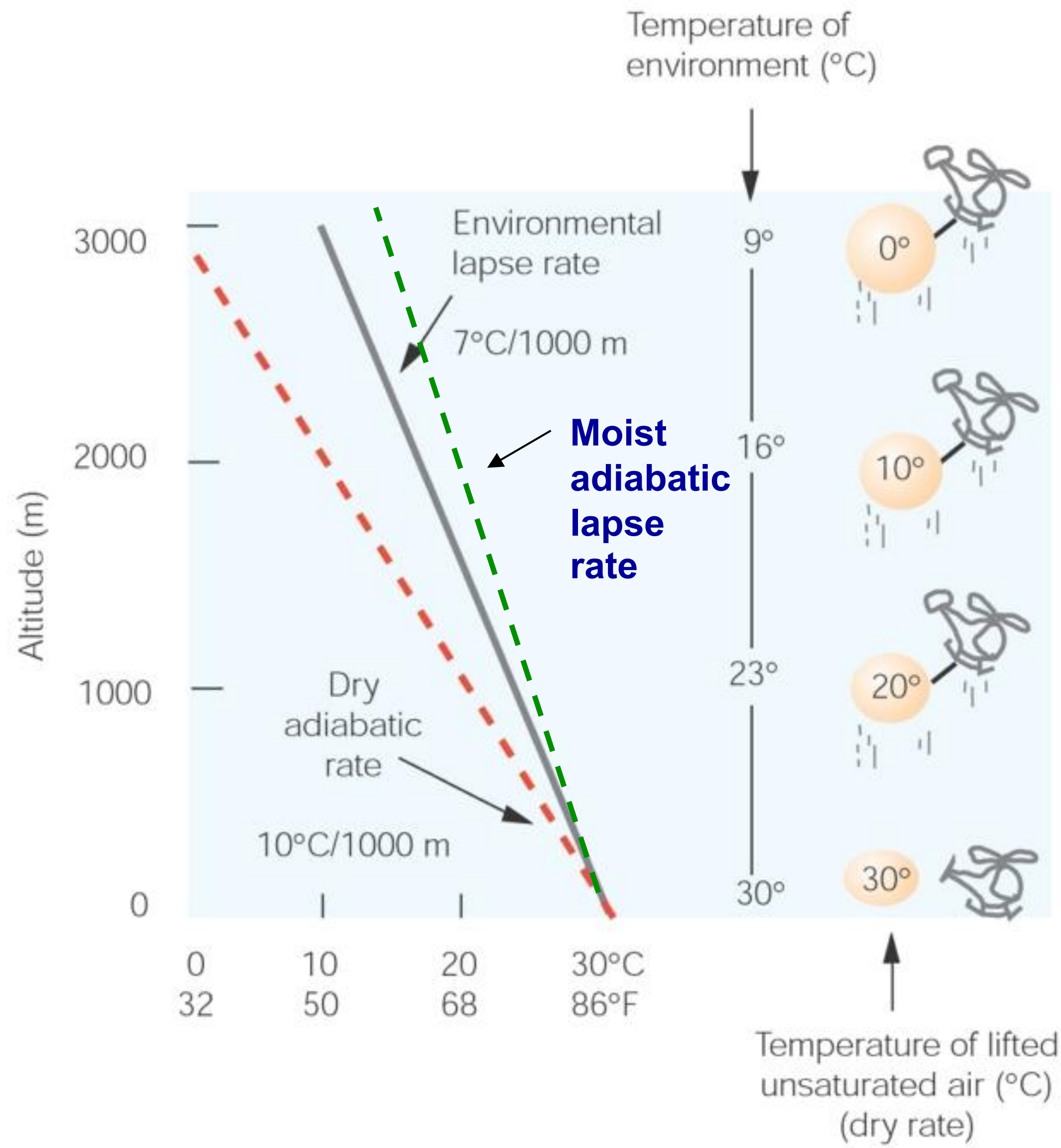
Cooling air aloft by clouds radiating energy or cold advection will also increase instability.

Conditionally Unstable

The atmosphere is conditionally unstable when the environmental lapse rate is between the dry and moist adiabatic lapse rates.

$$\Gamma_s < \Gamma < \Gamma_d$$

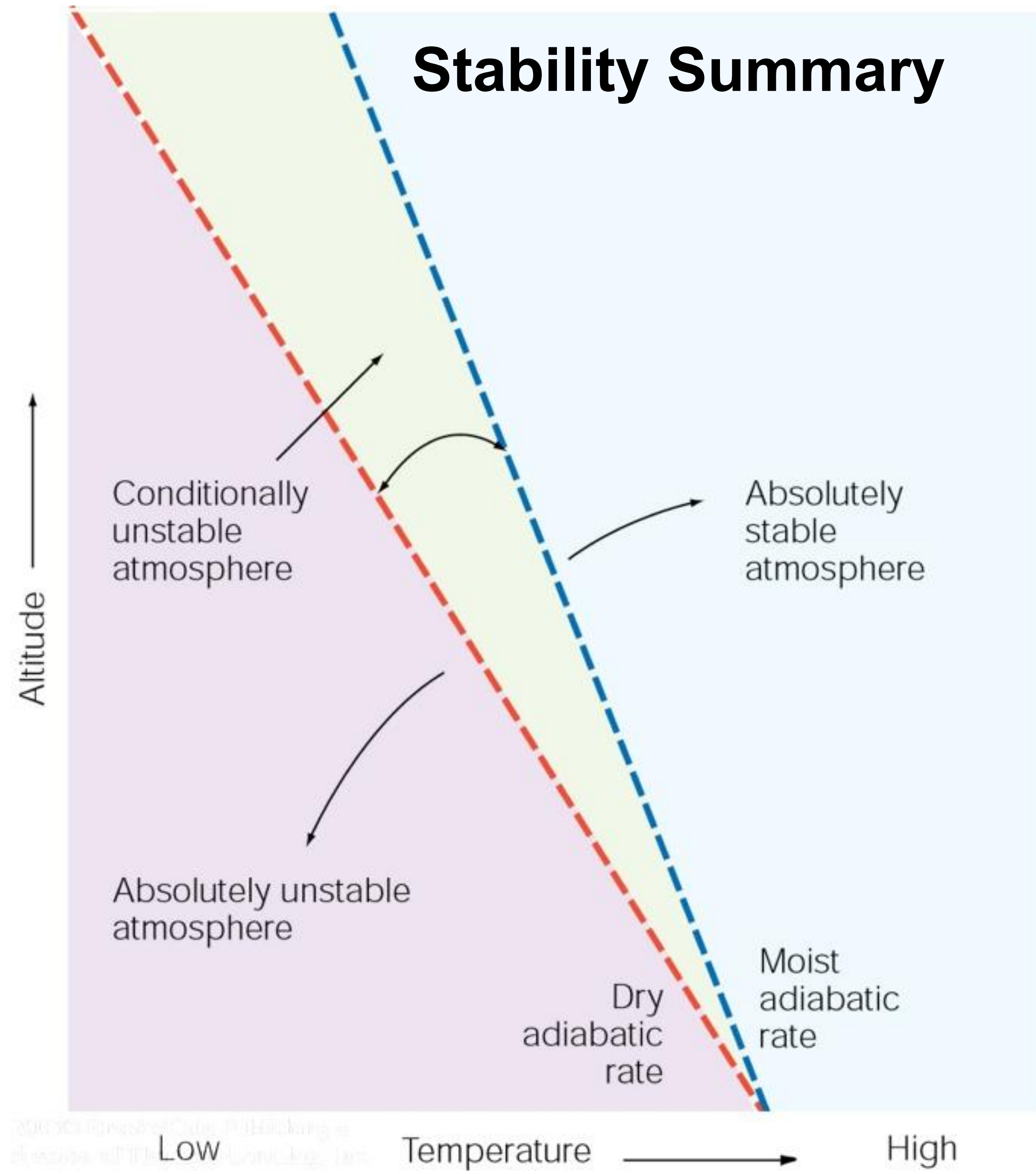
The atmosphere is stable with respect to unsaturated air, but is unstable with respect to saturated air



The unsaturated parcel of air at each elevation is colder than its surroundings. The atmosphere is stable with respect to unsaturated, rising air.

Environmental temperatures determine stability for rising parcels.

The atmosphere is **absolutely unstable** when the environmental lapse rate is steeper than the dry lapse rate, **absolutely stable** when the lapse rate is less steep than the moist lapse rate, and **conditionally unstable** otherwise.



Stability and lapse rate

Absolutely stable $\Gamma < \Gamma_s$

Absolutely unstable $\Gamma > \Gamma_d$

Conditionally unstable $\Gamma_d > \Gamma > \Gamma_s$

Neutral

$\Gamma = \Gamma_d$ for unsaturated air

$\Gamma = \Gamma_s$ for saturated air

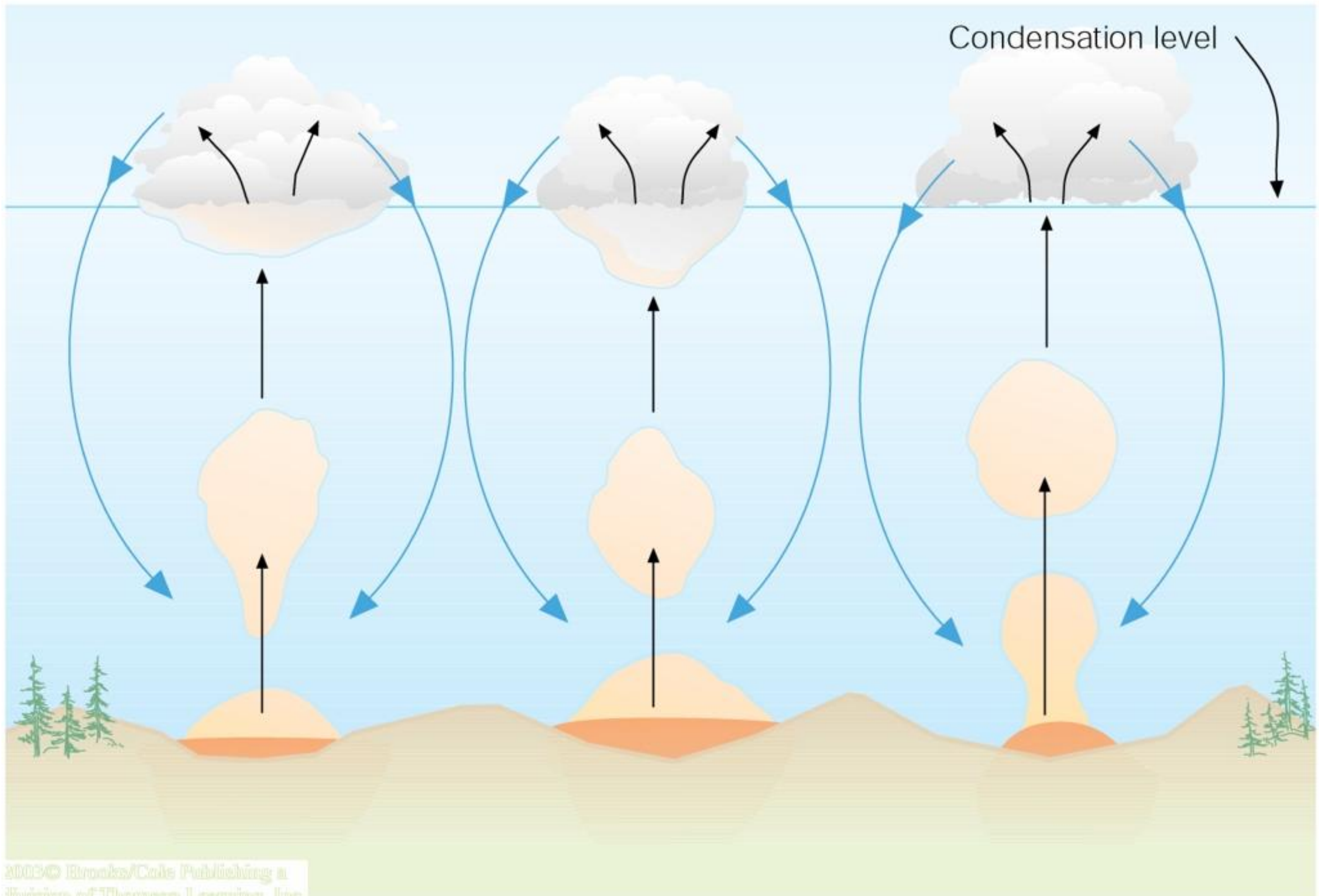
Cloud Development

- **Active**
  - occurs in unstable air
  - buoyancy force stimulates and sustains rising motion
  - air cools to saturation, cloud forms
  - condensation enhances buoyancy
  - large vertical dimension
- Passive
  - In stable air that suppresses vertical development
  - Saturation through
    - Large scale lifting -fronts, lows
    - Forced lifting - topography
    - Radiative cooling
  - Stratiform (layered) clouds

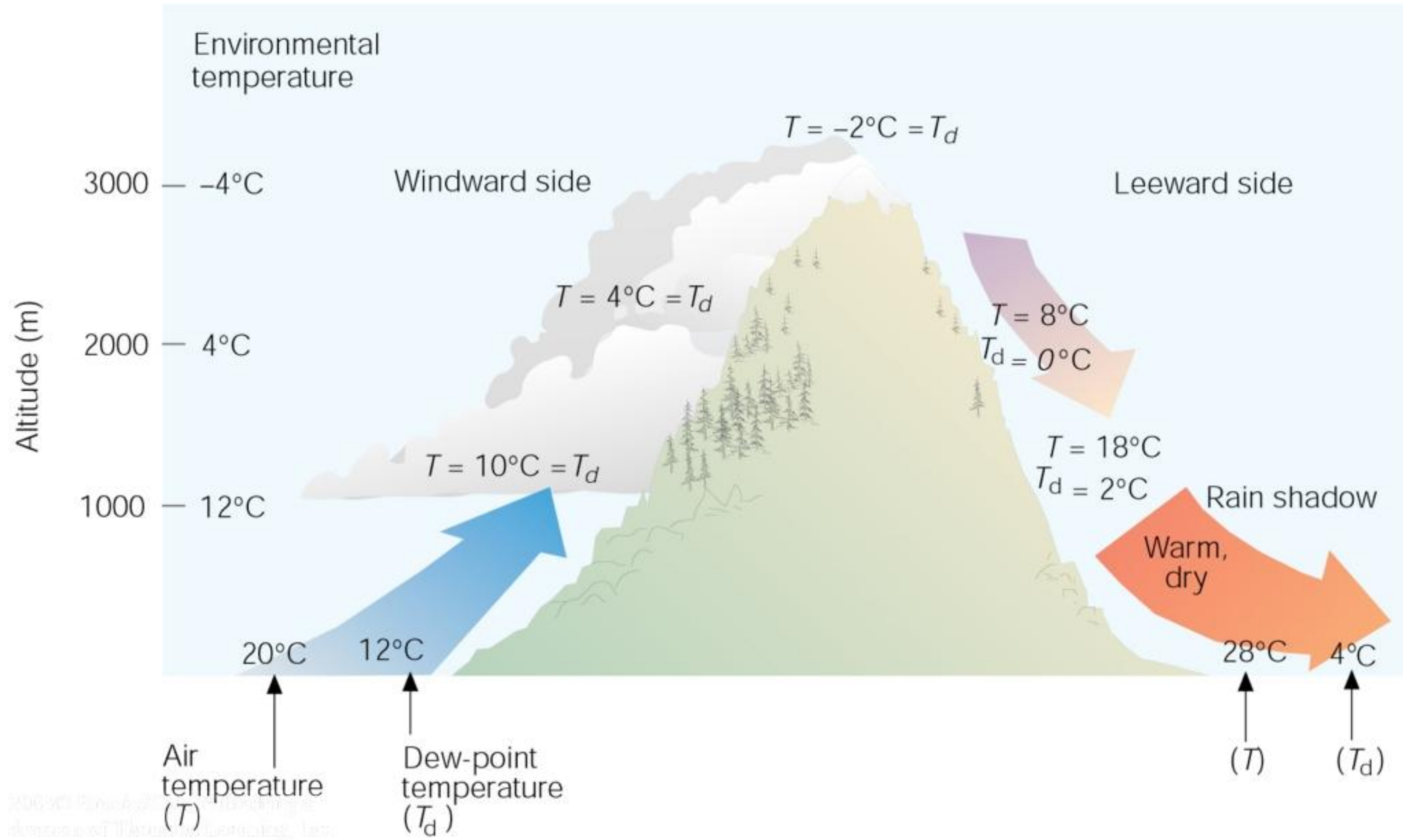
Convection & Clouds

Pockets of warm air rise as thermals with invisible water vapor, and at the dew point temperature condensation creates the cloud base.

Rising air from below is replaced by sinking air from above, creating areas of blue sky.



Topography & Clouds



Winds blowing moist air toward a mountain will experience orographic uplift to an elevation where dew point is reached and clouds are formed.

When the condensed moisture falls as rainfall, the leeward side of the mountain is kept in a rain shadow.

SUMMARY

1. **Stable air tends to resist upward vertical motions, clouds forming in a stable air will spread horizontally and have a stratified appearance.**

2. **An unstable atmosphere tends to favor vertical air currents and produce cumuliform clouds.**

3. **In a conditionally unstable atmosphere, rising unsaturated air may be lifted to a level where condensation begins, latent heat is released, and instability results.**

4. **The atmosphere is absolutely stable when the air at the surface is either cooler than the air aloft (an inversion), or the temperature difference between the warmer surface air and the air aloft is not very great, i.e., the environmental lapse rate is less than the moist adiabatic rate.**

5. **The atmosphere is absolutely unstable when the surface air is much warmer than the air aloft, i.e., the environmental lapse rate is greater than the dry adiabatic rate.**