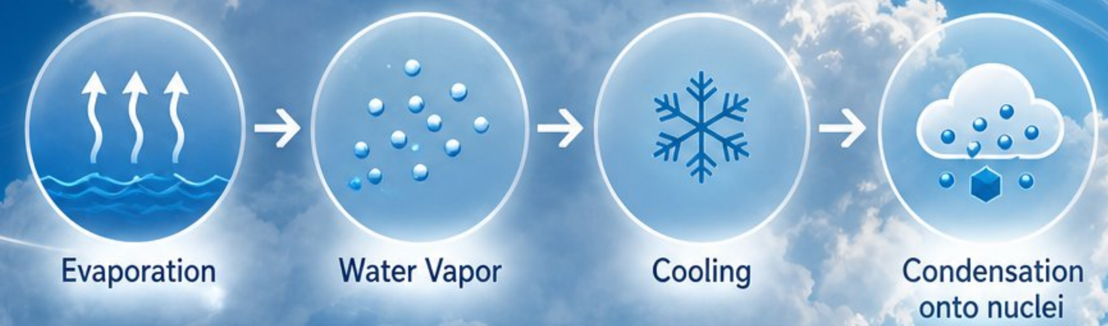
How Clouds Form: Water Vapor, Cooling, and Condensation

- Roadmap: evaporation → water vapor → cooling → condensation onto nuclei
- Explain how vapor cooling, CCN, and droplet/ice formation create clouds
- Applications: weather prediction, aviation, climate, sky observation
- Misconceptions: clouds are not steam; condensation releases latent heat

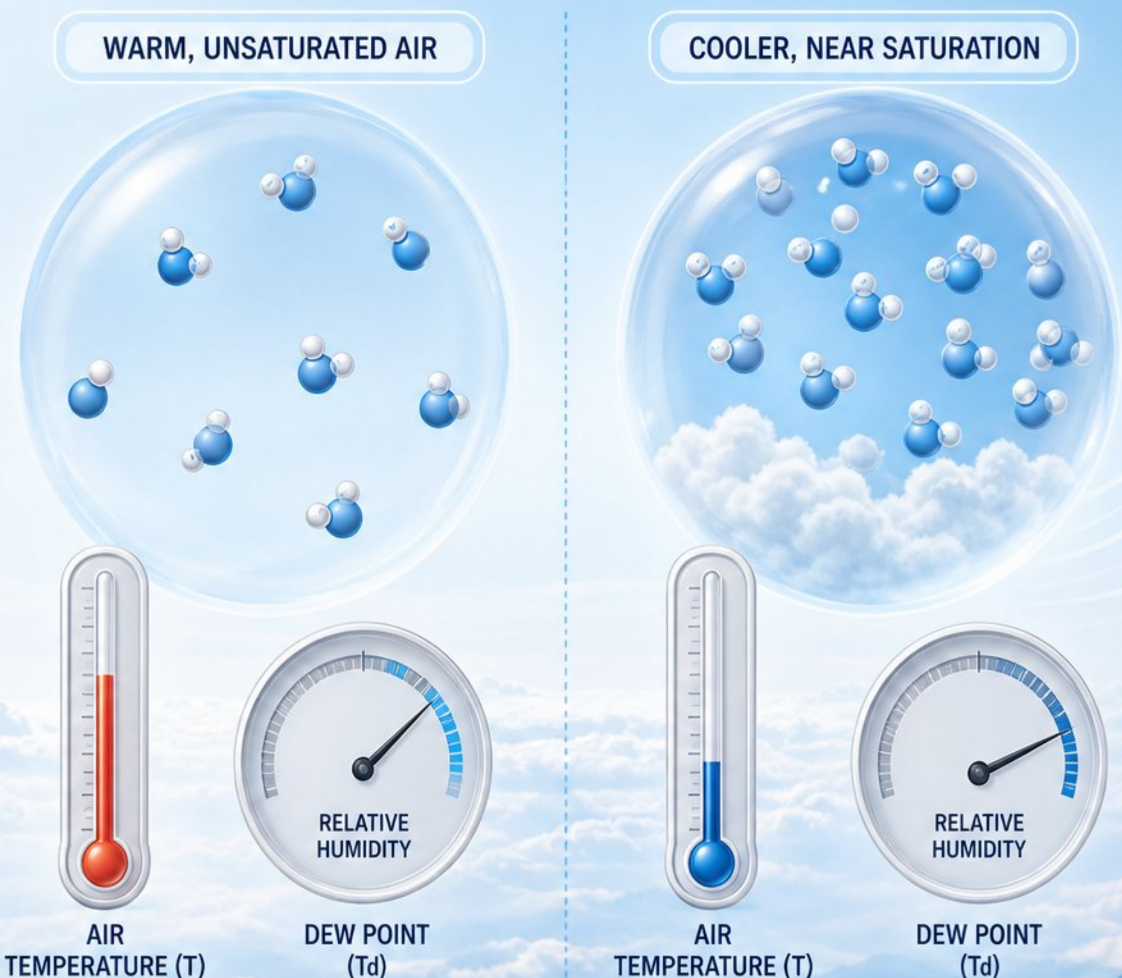


The Invisible Fuel: Water Vapor in the Atmosphere

- Water vapor enters the air via ocean/lake evaporation, plant transpiration, and ice/snow sublimation
- It is an invisible gas, distinct from visible liquid water droplets or ice crystals
- Vapor pressure (e) measures water vapor's partial pressure; saturation vapor pressure (e_s) is the max possible at a given temperature
- The Clausius-Clapeyron equation shows e_s increases rapidly with temperature—warmer air can hold much more moisture

Measuring Moisture: Humidity and Dew Point

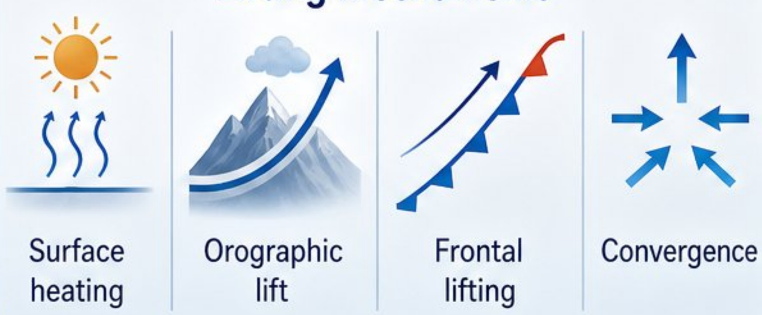
- **Absolute measures:** vapor pressure, mixing ratio, and specific humidity quantify actual water vapor
- **Relative Humidity** (RH = e/es × 100%) indicates how close air is to saturation, not total water content
- **Dew point temperature** (Td): the temperature where saturation occurs—key to estimating cloud base
- **Dew point depression** (T – Td) shows how much cooling is needed to reach saturation

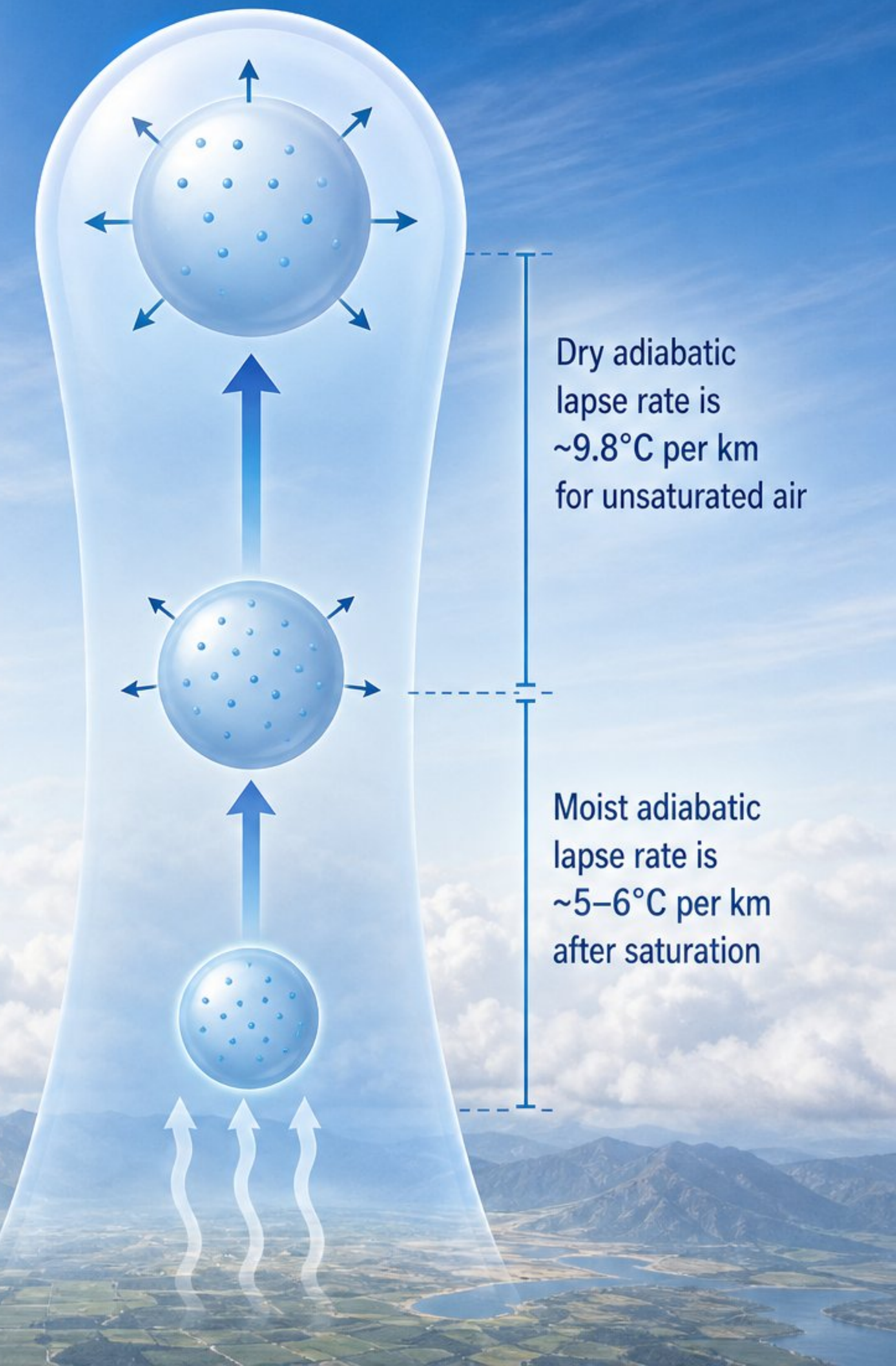


Cooling the Air: Pathways to Saturation

- - Rising air expands in lower pressure and cools adiabatically
- - Dry adiabatic lapse rate is ~9.8°C per km for unsaturated air
- - Moist adiabatic lapse rate is ~5–6°C per km after saturation
- - Lifting mechanisms: surface heating, orographic lift, frontal lifting, convergence

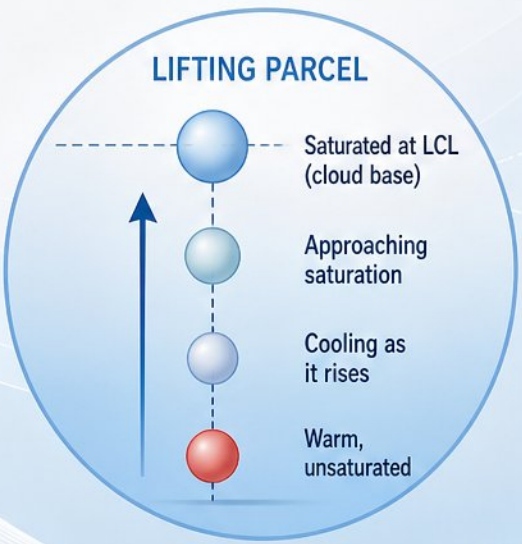
Lifting Mechanisms

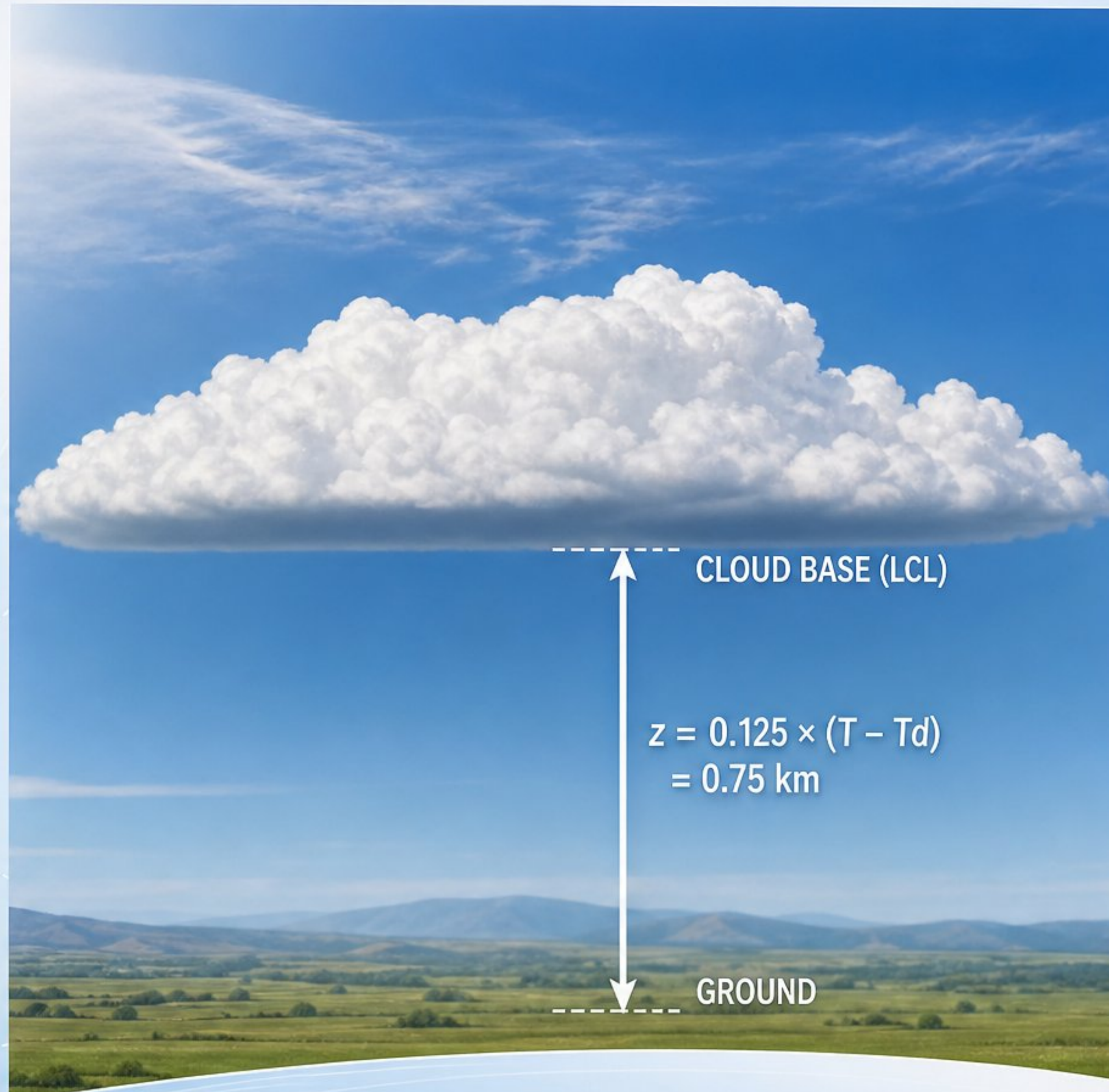




From Dew Point to Cloud Base: The Lifting Condensation Level

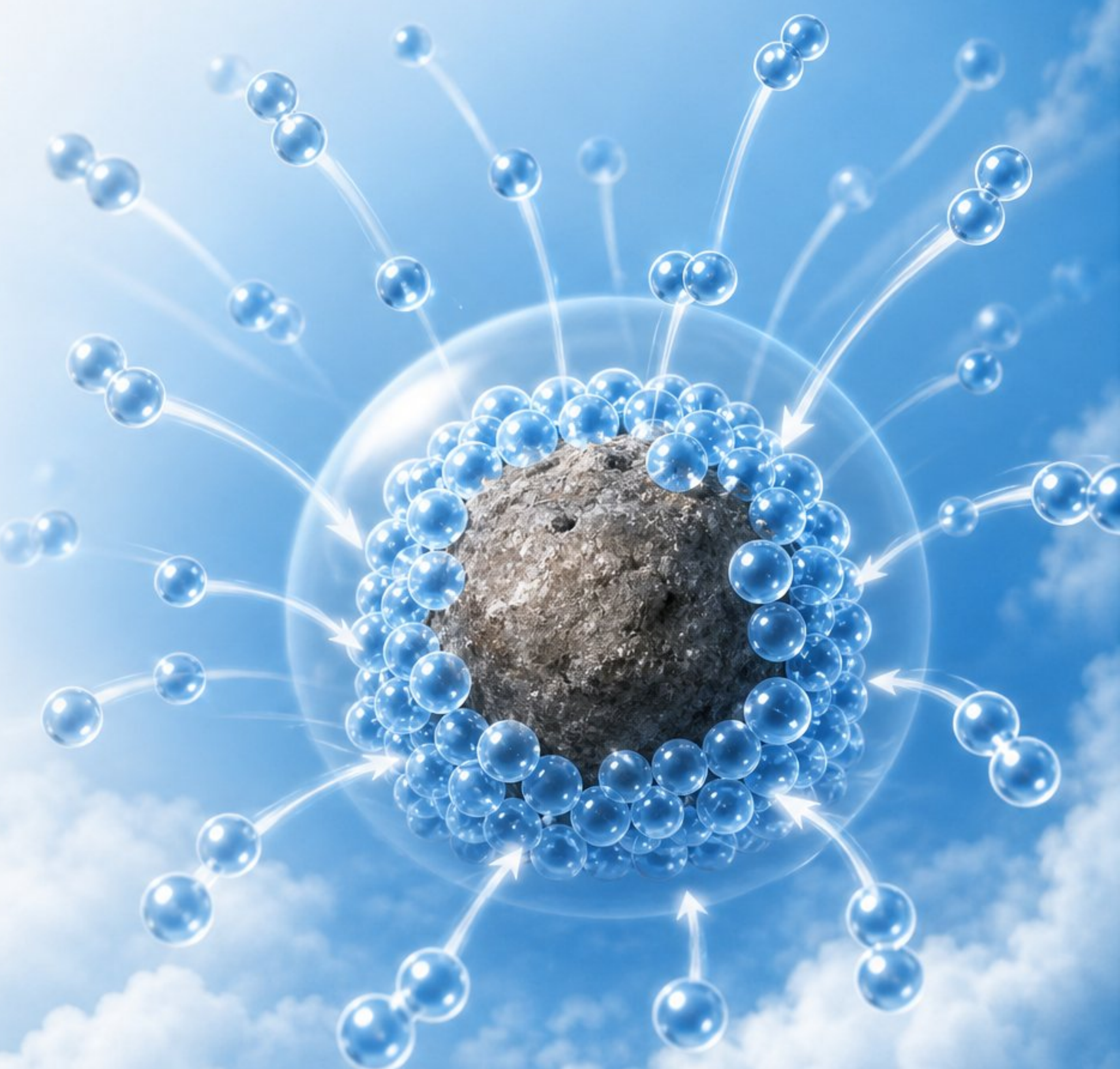
- LCL is the height where a rising air parcel cools to saturation
- Cloud-base formula: $z = 0.125 \times (T - T_d)$ km
- Example: T = 20 °C, Td = 14 °C gives cloud base at 0.75 km
- Flat cumulus bases directly visualize the LCL altitude





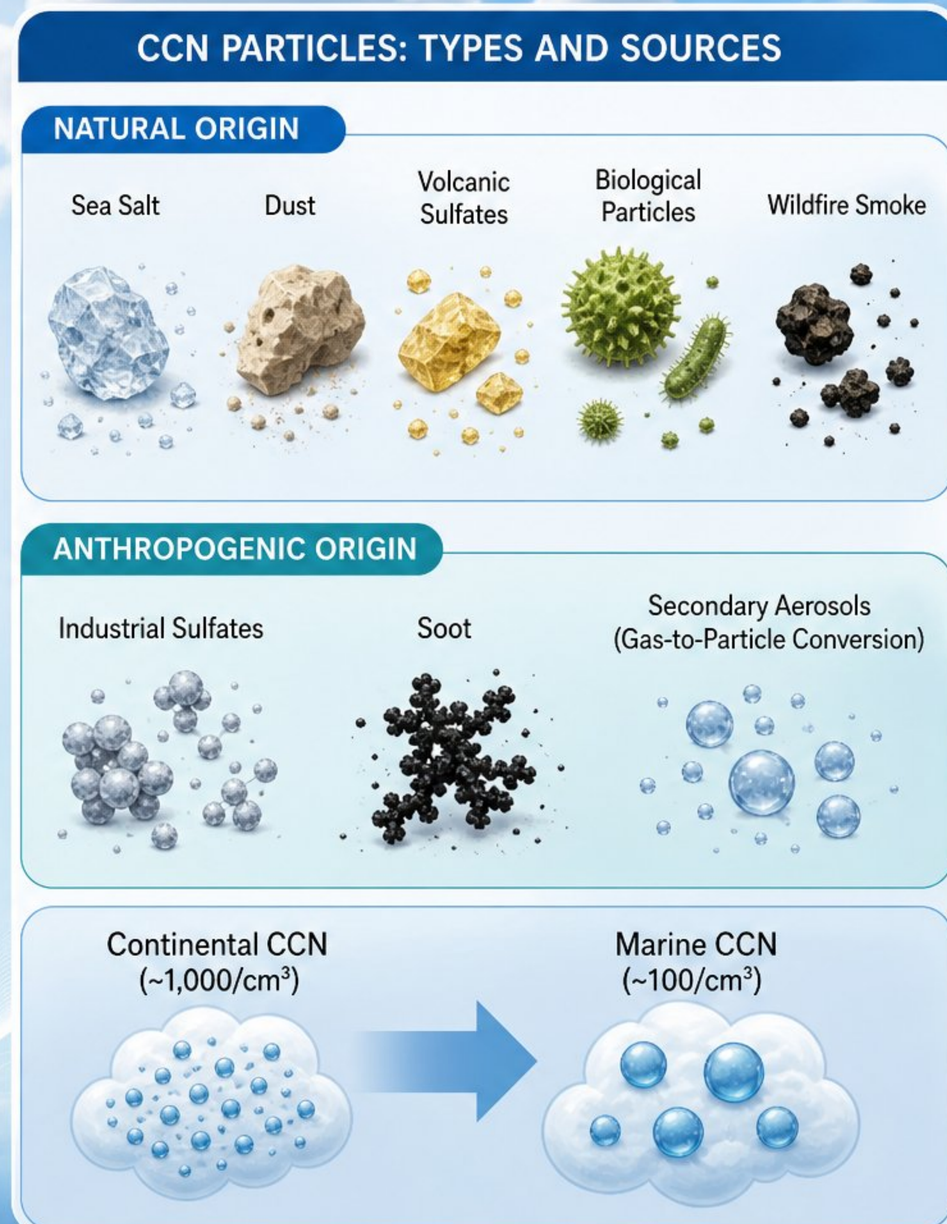
The Nucleation Problem: Why Water Vapor Needs a Surface

- **Homogeneous nucleation:** spontaneous droplet formation requires extreme supersaturation (RH ~300%)—virtually impossible in real atmosphere
- **Heterogeneous nucleation:** water vapor condenses onto existing atmospheric particles called cloud condensation nuclei (CCN)
- **CCN** are a subset of aerosols, typically 0.1–1 μm in diameter, that provide the necessary surface for condensation
- Every cloud droplet forms on a CCN; without nuclei, no visible clouds can exist



Types and Sources of Cloud Condensation Nuclei

- Natural CCN: sea salt, dust, volcanic sulfates, biological particles, wildfire smoke
- Anthropogenic CCN: industrial sulfates, soot, secondary aerosols (gas-to-particle conversion)
- Hygroscopic (soluble) vs. hydrophobic particles; solubility enables droplet activation
- Continental CCN (~1,000/cm^3) yield more, smaller droplets than marine CCN (~100/cm^3)



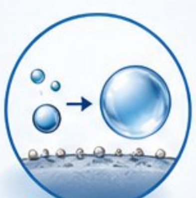
Köhler Theory: Curvature, Solutes, and Droplet Activation

- Kelvin (curvature) effect raises equilibrium vapor pressure over small droplets

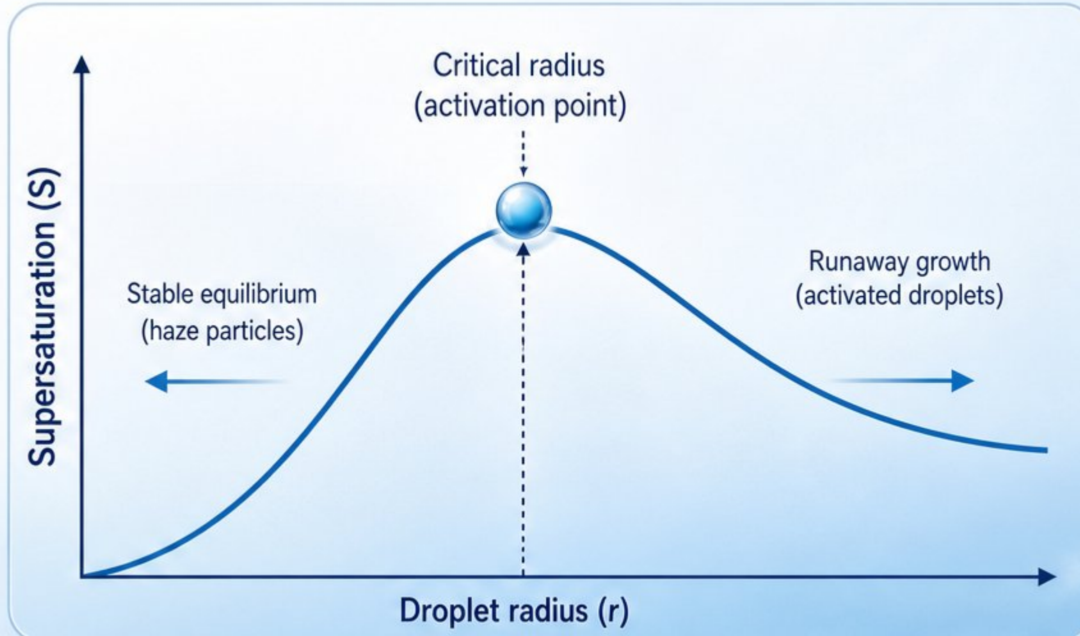
- Raoult (solute) effect lowers vapor pressure by dissolved CCN material

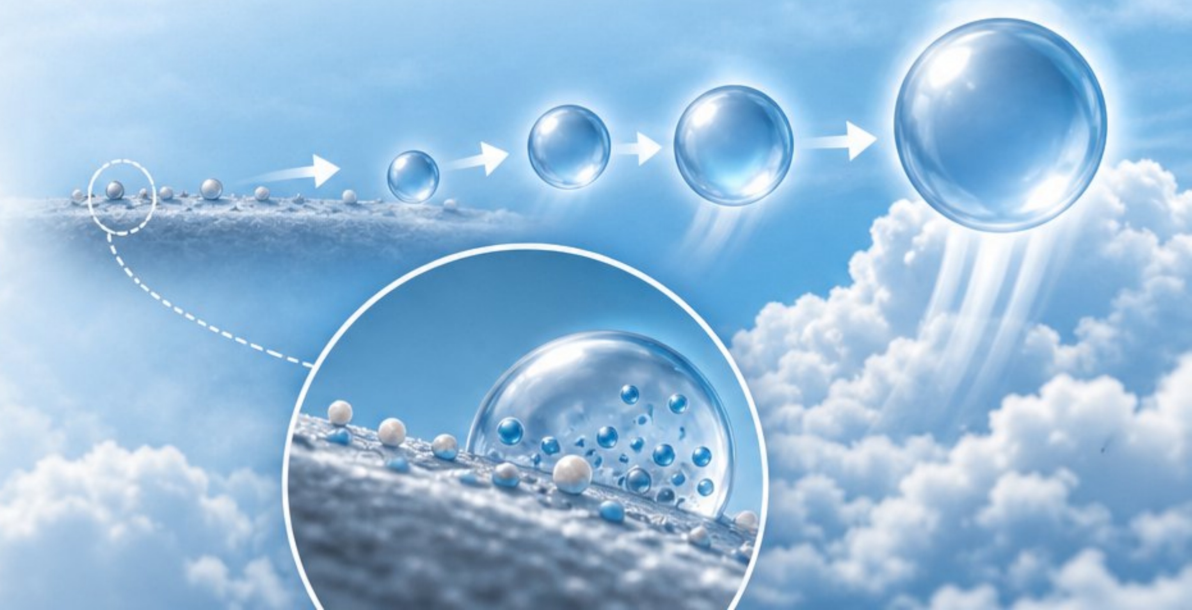
- The Köhler curve shows supersaturation vs. droplet radius; the peak defines the activation barrier

- Haze particles exist in stable equilibrium below 100% RH; activated droplets grow freely above the critical supersaturation

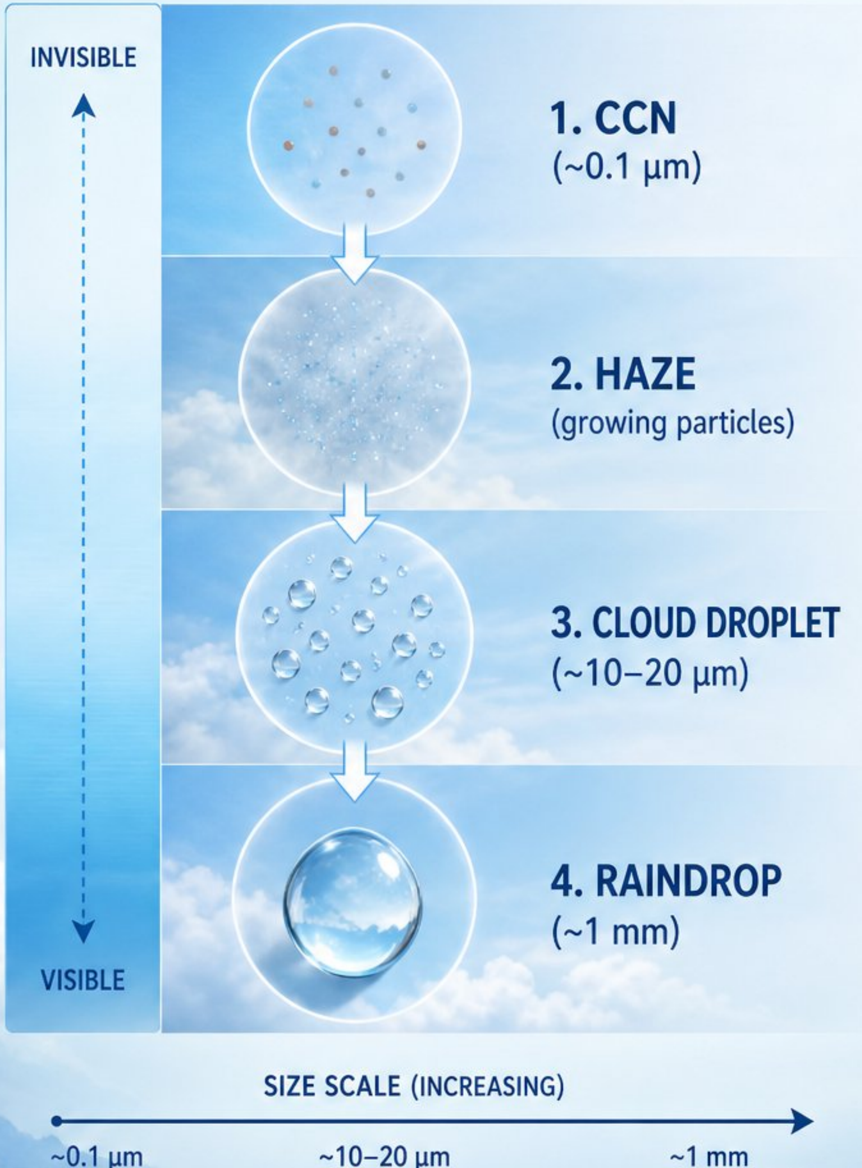


- Larger or more hygroscopic CCN activate first at lower supersaturations





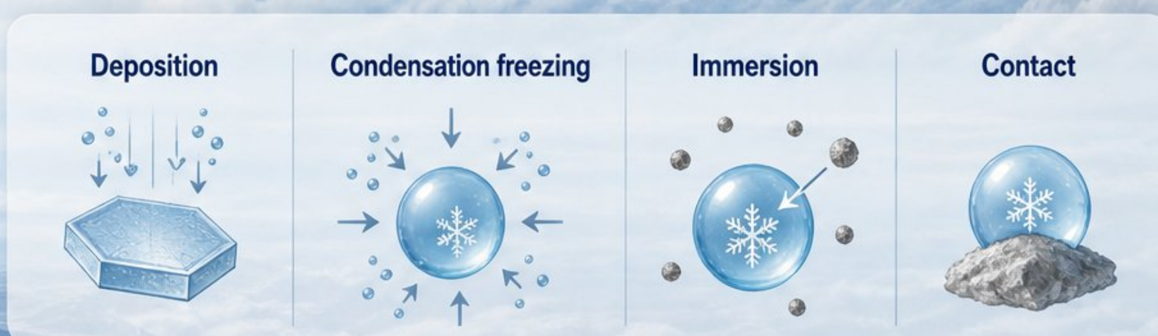
From Vapor to Droplet: The Condensation Process Step by Step



- Air rises → expands → cools → RH reaches 100% → water vapor condenses onto CCN
- Initial rapid growth by vapor diffusion; slows as droplets compete for water vapor
- CCN (~0.1 μm) → cloud droplet (~10–20 μm) → raindrop (~1 mm)
- Latent heat release warms the parcel, adding buoyancy and fueling continued lift
- Droplet fall speeds (~1 cm/s) are far less than typical updrafts, keeping clouds aloft

Below Freezing: Supercooled Water and Ice Nuclei

- Warm clouds (liquid only) vs. cold clouds (mixed-phase or fully glaciated)
- Supercooled water: liquid droplets persist down to ~−40 °C
- Ice nuclei (IN) are far scarcer than CCN, enabling supercooled clouds
- Modes of ice nucleation: deposition, condensation freezing, immersion, contact

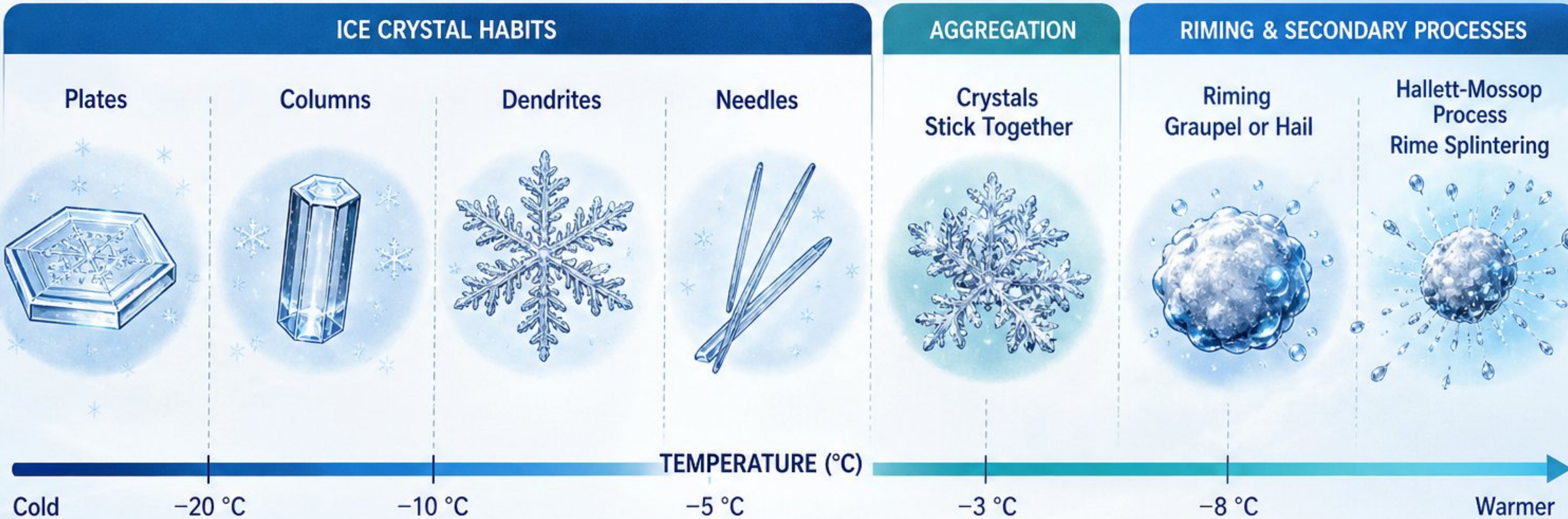


Ice Crystal Growth:

The Wegener–Bergeron–Findeisen Process

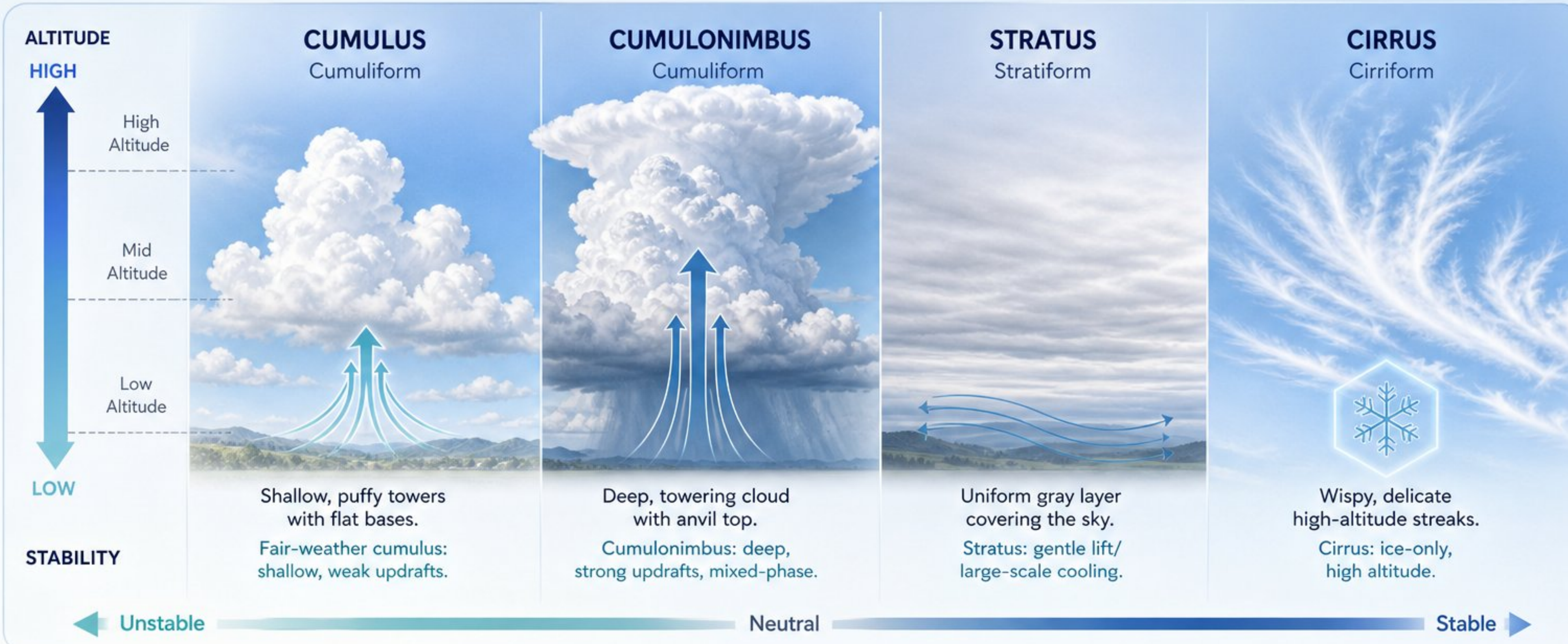
- \- Saturation vapor pressure over ice is lower than over liquid water at subfreezing temperatures.
- \- In mixed-phase clouds, ice crystals grow at the expense of evaporating supercooled droplets.
- \- The WBF process occurs when ambient vapor pressure falls between the ice and liquid saturation curves.
- \- Results in rapid ice crystal growth to precipitation sizes, often leading to complete cloud glaciation.

Ice Crystal Habits and Secondary Ice Production



- Ice crystal shape depends on temperature and supersaturation: plates, columns, dendrites, needles
- Aggregation: crystals stick together near −5 °C, accelerating growth
- Riming: supercooled droplets freeze on contact, forming graupel or hail
- Hallett-Mossop process: rime splintering at −3 to −8 °C multiplies ice crystal numbers

Reading the Sky: What Clouds Tell Us About Atmospheric Processes



- Cumuliform = convection (vertical), Stratiform = layer (horizontal), Cirriform = ice (wispy)
- Cloud type controlled by updraft strength, atmospheric stability, and moisture supply
- Fair-weather cumulus: shallow, weak updrafts. Cumulonimbus: deep, strong updrafts, mixed-phase
- Stratus: gentle lift/large-scale cooling. Cirrus: ice-only, high altitude
- Cumulus base = visual LCL; cloud top height reflects atmospheric stability

INVISIBLE — INVISIBLE TO VISIBLE SPECTRUM → VISIBLE

The Full Chain: Linking Vapor, Cooling, Nuclei, and Cloud Types

WATER SOURCE
Oceans, lakes, rivers, soil, vegetation

VAPOR
Water evaporates and enters the air

COOLING
Rising air expands and cools adiabatically

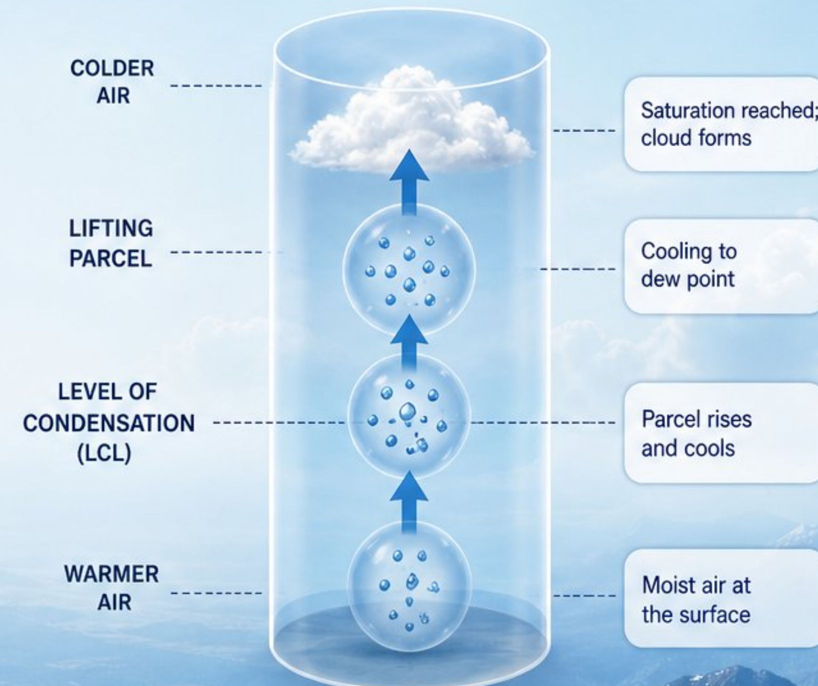
SATURATION
Air reaches 100% relative humidity (dew point)

CCN ACTIVATION
Cloud Condensation Nuclei (CCN) become activated

DROPLET/ICE GROWTH
Droplets collide and coalesce; ice crystals grow (e.g., WBF process)

VISIBLE CLOUD
Clouds are visible collections of liquid droplets or ice crystals

- Water source → vapor → cooling → saturation → CCN activation → droplet/ice growth → visible cloud
- Key terms: relative humidity, dew point, adiabatic cooling, CCN, LCL, supercooled water, WBF process
- Clouds are liquid droplets or ice crystals, not water vapor
- Condensation releases latent heat, warming the parcel
- Different cloud types form under different stability, moisture, and updraft conditions



Summary and Beyond: From Clouds to Weather

- Clouds require water vapor, cooling, and condensation nuclei
- Use these three pillars to explain any cloud type
- Next: droplet growth, precipitation, and climate impacts
- Every cloud reveals invisible atmospheric processes

INVISIBLE — INVISIBLE TO VISIBLE → VISIBLE