ESS 431 PRINCIPLES OF GLACIOLOGY
ESS 505 THE CRYOSPHERE

ACCUMULATION 1: CLOUD PHYSICS AND ICE CRYSTAL FORMATION

OCTOBER 08, 2018

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Field trip Saturday – weather dependent

Housekeeping for the day

Field trip

- Risk Acknowledgement forms (online, on field-trip page)
  You need to sign this form to go on the trip.
  Please print, sign, and bring on Wednesday (Friday at latest).
- Equipment – boots, raingear, warm clothes, lunch, (hand lens)
- Safety procedures on the trip (online, see fieldtrip page).
- Directions to trailhead – posted on fieldtrip page.
- We will circulate sign up list on Wednesday (please decide before class on Wednesday) circulating list

Reading Assignments – linked on website
Friday Discussion/Lab Section – 2:30-3:50 here
Homework – it is posted online
Lecture – Posted online following class

Sources

USDA Beltsville Agriculture Research Center
http://emu.arsusda.gov/snowsite/

SnowCrystals.com, Kenneth G. Libbrecht, Caltech
http://www.its.caltech.edu/~atomic/snowcrystals/photos/photos.htm

H. Uyeda, Snow Crystal Gallery, Hokkaido University
http://radar.sci.hokudai.ac.jp/crystal/gallery.html

Andy Radin
http://www.fourfa.com/photo/Galleries/Canada/index.html

NOAA
http://www.photolib.noaa.gov/historic/nws/index.html

Lecture notes from C.F. Raymond and S.G. Warren

Let’s check out Ice I_h model

Details matter for cloud physics

Snow in the Atmosphere

The Big Picture

- Water vapor → water droplets
- Water droplets → ice crystals
- Ice crystals grow

Relative Humidity (RH)

Clouds form when air becomes supersaturated.
Think of vapor in contact with liquid water.

e = water vapor pressure

$e_s(T)$ = equilibrium or saturation vapor pressure

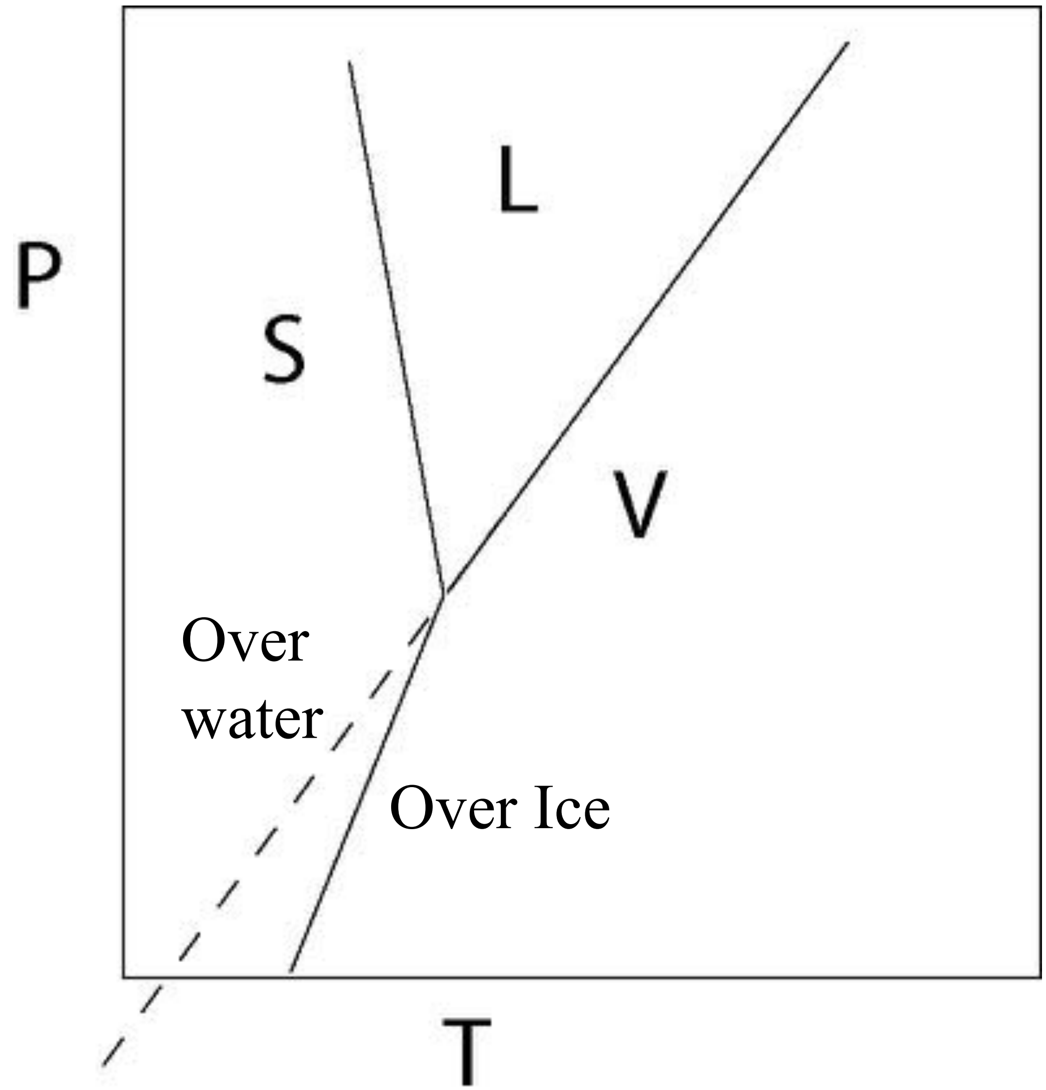
This is the vapor pressure required at temperature T so that equal numbers of molecules leave and re-enter the liquid.

$RH = e/e_s(T)$ is normally in range 0-100%

RH over Ice

We could also find $e_s(T)$ over ice

- Lower than over water
- Why?



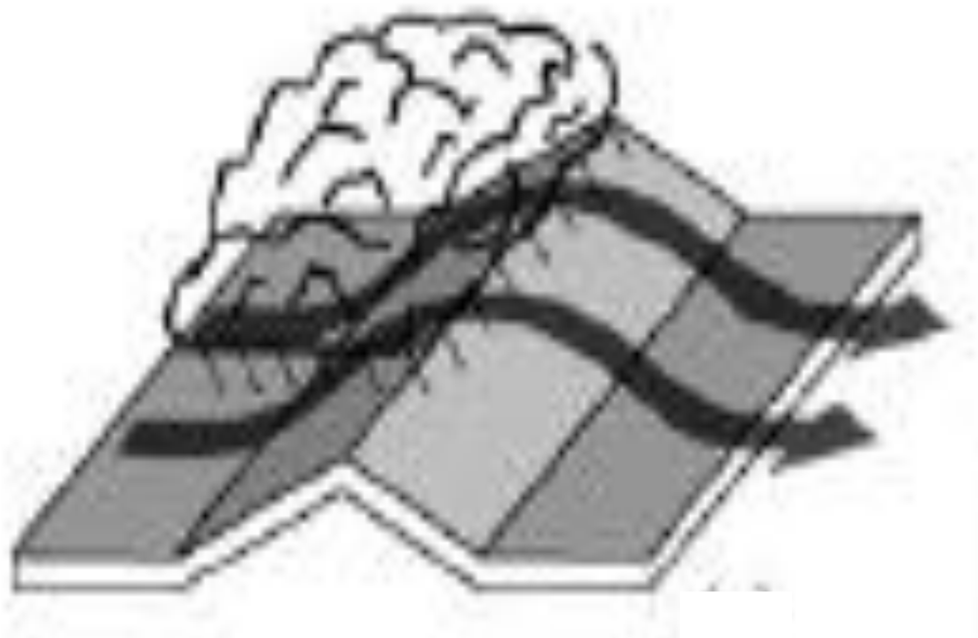
Cloud Formation

Clouds form when cooling air becomes super-saturated

Air cools as it rises

- Orographic uplift
- Frontal activity
- Convection
- Cyclones

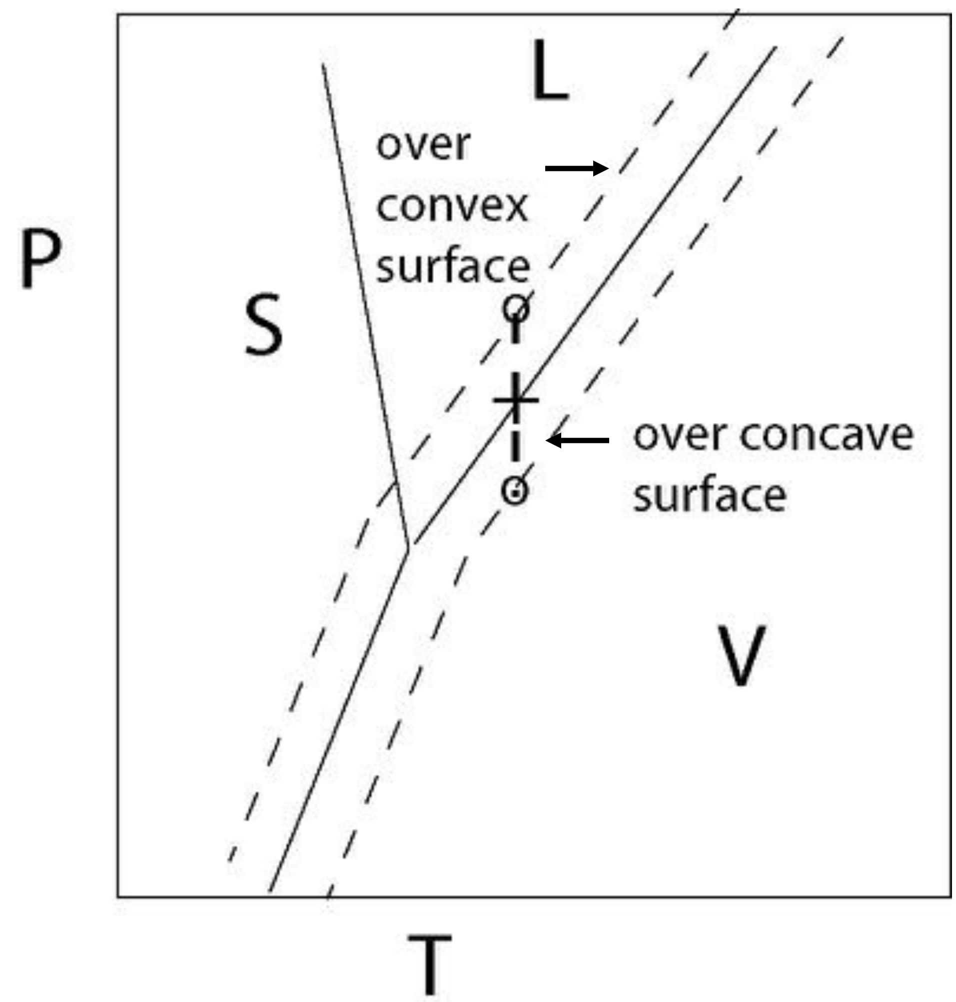
•On Antarctic Plateau, 80% of precipitation is diamond dust formed by orographic cooling



From G. Roe

Droplet Curvature

- Molecule on a flat surface has 3 or 4 H bonds
- Molecules on corners are held by only 2 H bonds
- It' s easier to break off corner molecules
- $e_s(T)$ must be higher to drive equal number of molecules back onto convex surface at a given temperature T



Problems with High-Curvature Drops

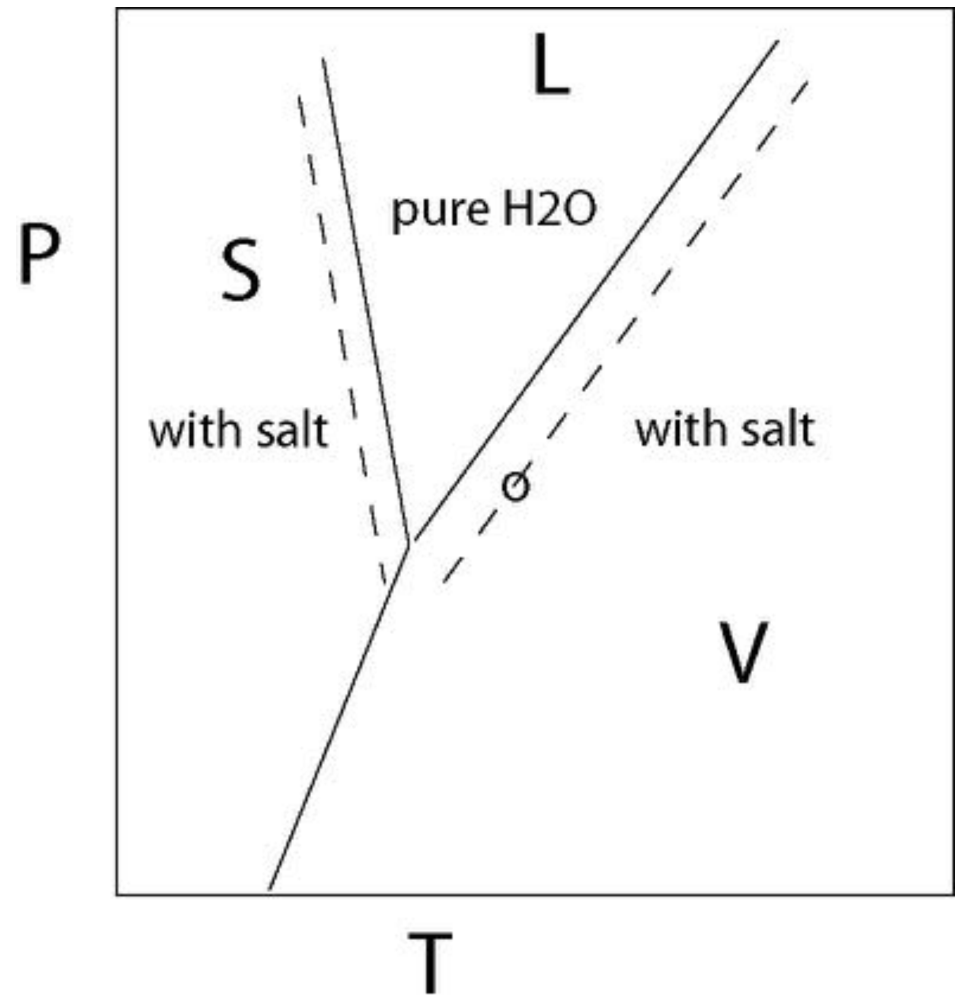
- High vapor pressure (super-saturation) is needed to maintain very small drops of pure H_2O

- Very small drops of pure H_2O would evaporate

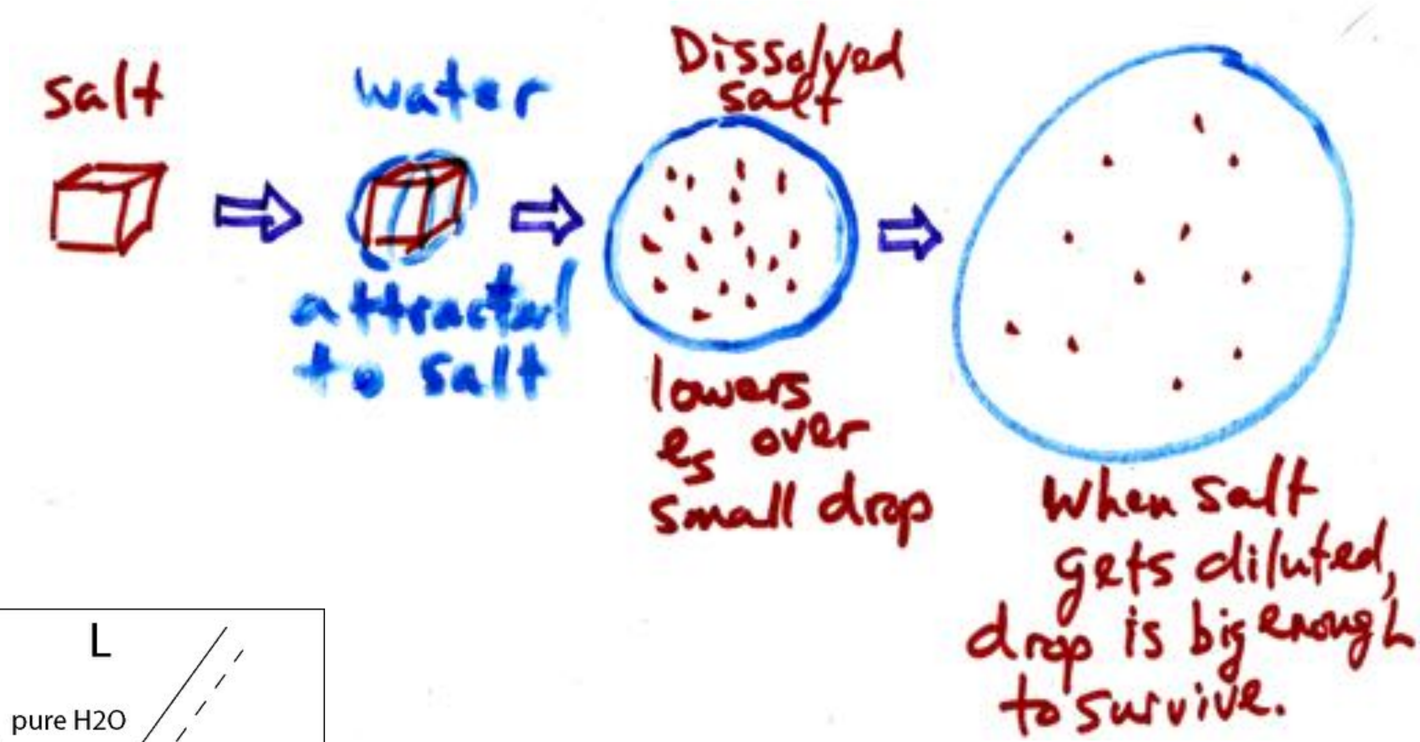
- Typical limit to super-saturation in clouds is 100.5%

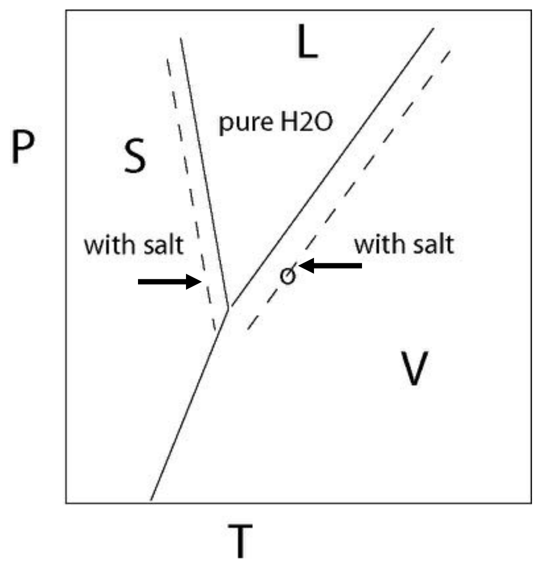
Effect of Salt

- Salt dissolves in water, but not in ice or vapor, i.e. salt stays in the liquid.
- Dissolved salt is highly charged (Na^+, Cl^-)
- H_2O is polar; neg. arms are attracted to Na^+, pos. arms attracted to Cl^-, i.e. it is hard to get H_2O molecules to leave the liquid phase.
- $e_s(T)$ must be lowered to avoid driving more molecules back into salty water than are leaving at a given temperature T



Cloud Condensation Nuclei (CCN)





- e_s(T) is reduced over a salt water drop
- A small salty drop can survive without evaporating

Characteristics of CCN

- Soluble aerosol particles facilitate condensation
- Usually salts
- Very common in the atmosphere
  typically 10^1-10^3 cm^{-3}
- Typical aerosol radius $R \sim 0.1 \mu m$
- Typical drop radius $R \sim 10\ \mu m$
- So aerosol is ultimately very diluted (10^{-6})

Sources of CCN

- Sea salt (from spray)
- Wind-blown organic "bits"
- Sulfate H_2SO_4 partly neutralized by ammonia NH_3

Sources of sulfur over oceans:

- Volcanoes SO_2, H_2S
- Oceanic algae make dimethyl sulfide (DMS) $CH_3\ S\ CH_3$

Sources of CCN

Sources of sulfur over land

- Volcanoes – SO_2, H_2S

- Soil microbes make DMS, other compounds

$CH_3\ S\ CH_3 \rightarrow SO_2 \rightarrow SO_3 \rightarrow H_2SO_4 \rightarrow (NH_4)_2SO_4$

and $(NH_4)_2SO_4$ is a water-soluble salt

Feedback in a warming climate?

Suppose the ocean gets warmer (it is …)

- DMS is created by various algae
- the most prolific producer lives under sea ice

- What feedback processes on cloud formation might you anticipate?

How does a snowflake start?

A drop of pure water can be super-cooled to -37^oC
Ice crystals can form just below 0^oC
What's going on?

- At 0^oC, 85% of H-bonds are made
- Water stays liquid until it can make 1-2 more H-bonds
- In absence of external points for molecules to attach to, "homogeneous freezing" occurs at - 37^oC.

- Heterogeneous freezing can occur near 0^oC when water is in contact with "nucleation points".

Characteristics of Ice Nuclei (IN)

•Heterogeneous freezing can occur near $0^{o}C$ when water is in contact with "nucleation points"

•Are there "things" in the atmosphere that can nucleate ice crystals?

IN must be:

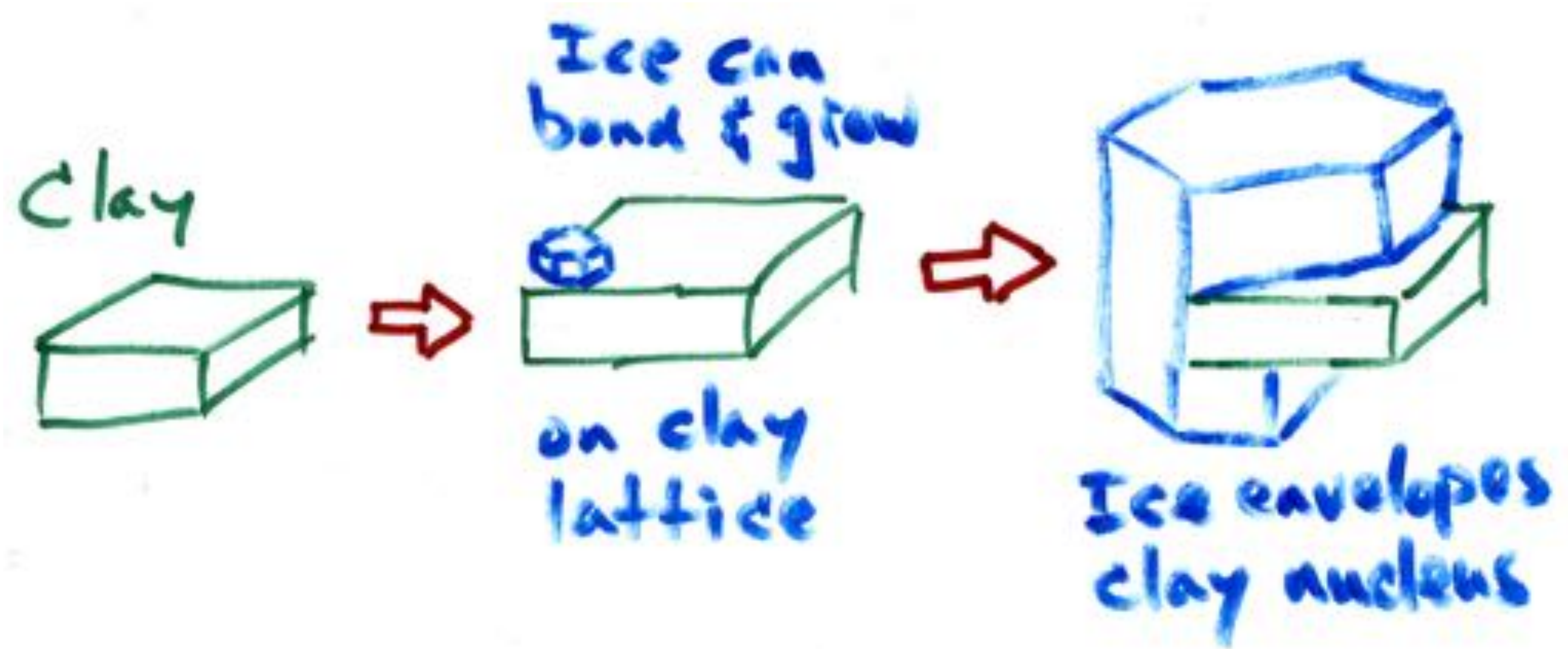
- Insoluble in water
- Capable of H-bonding
- Have lattice spacing similar to spacing in ice I_h ($\sim 10^{-10}$ m)
- Have hexagonal symmetry

Some Ice Nuclei (IN)

Material	Nucleation Threshold
Ice	$0^{o}C$
Silver iodide (Ag I)	$-4^{o}C$
Clay minerals in dust/soil	$-10^{o}C$
Vegetation litter, bacteria	$-4^{o}C$ and colder

Ice Growth on "Clean" Clay

- Water vapor can bond (poorly) to clay crystal lattice
- That's good enough to get an ice crystal started



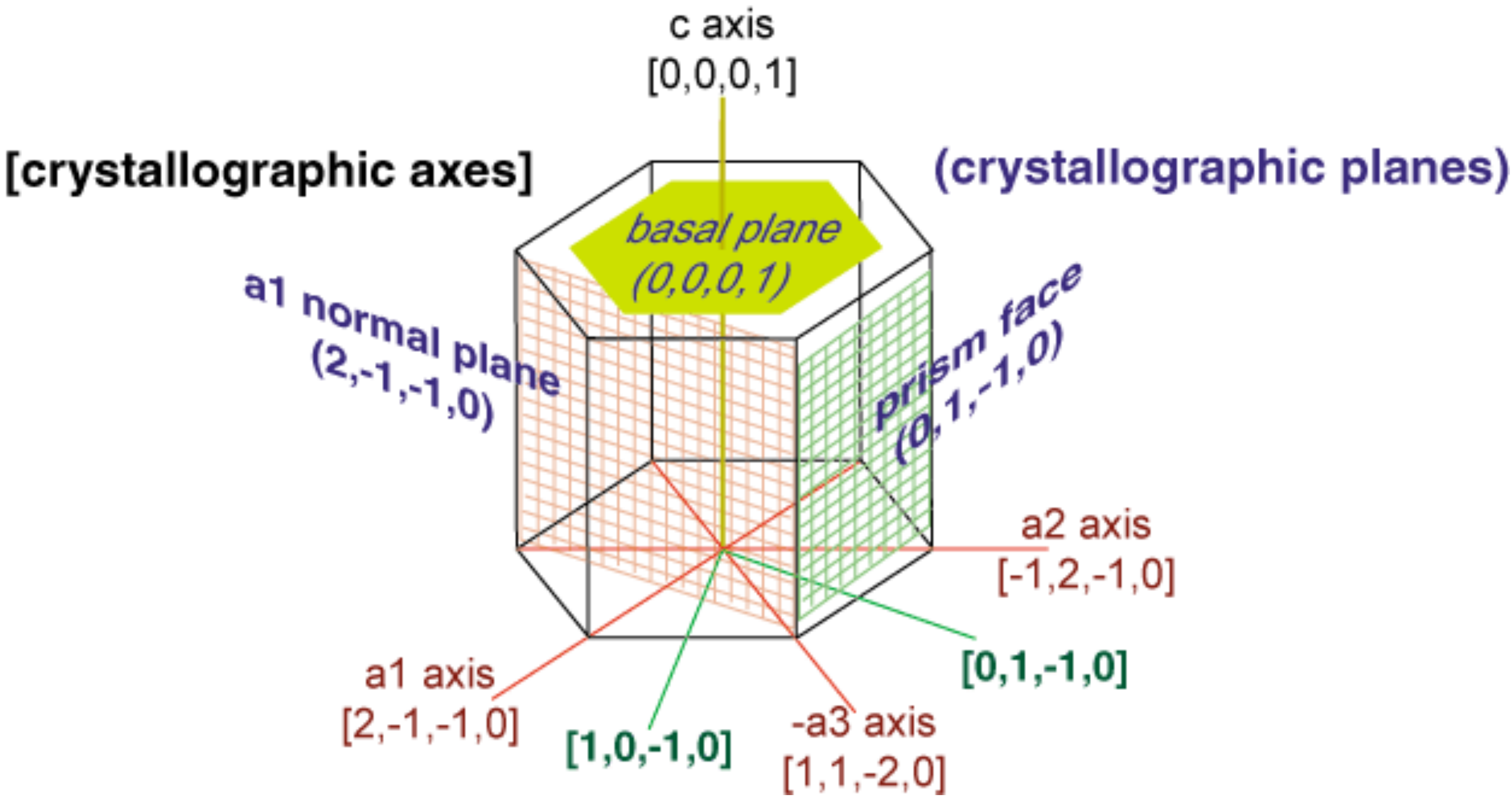
Ice Growth on Salty Clay

- First, salt attracts water
- Then water can freeze to clay crystal lattice
- Finally, more ice grows on existing ice crystal
- Ice overwhelms clay particle

CCN vs IN

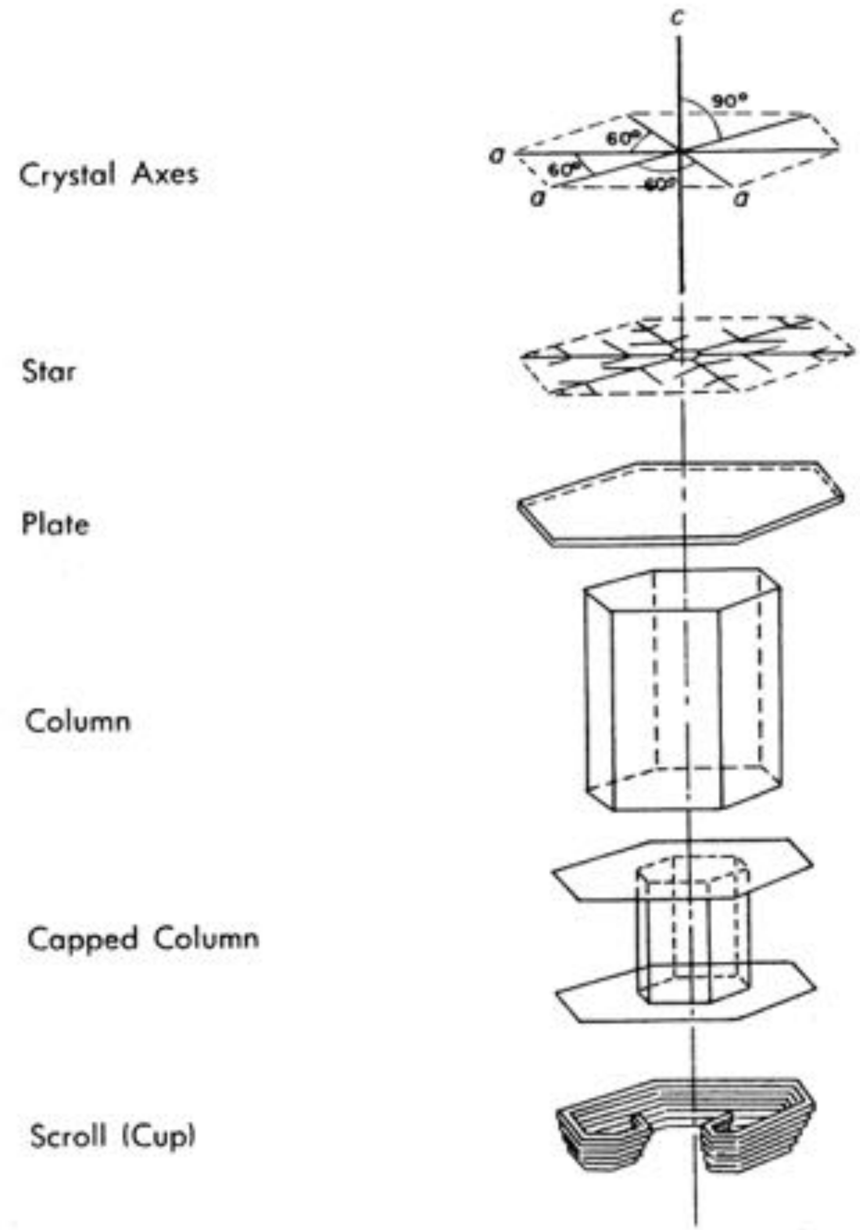
Cloud Condensation Nuclei		Ice Nuclei	
Small	(0.1 μm)	Large	1 μm
Soluble	(salt)	Insoluble	(dust)
Common	(10^1-10^3 cm^{-3})	Rare	(10^1-10^3 cm^{-3})
	(10^6 $liter^{-1}$)		(10^1 $liter^{-1}$)

Ice-Crystal Axes



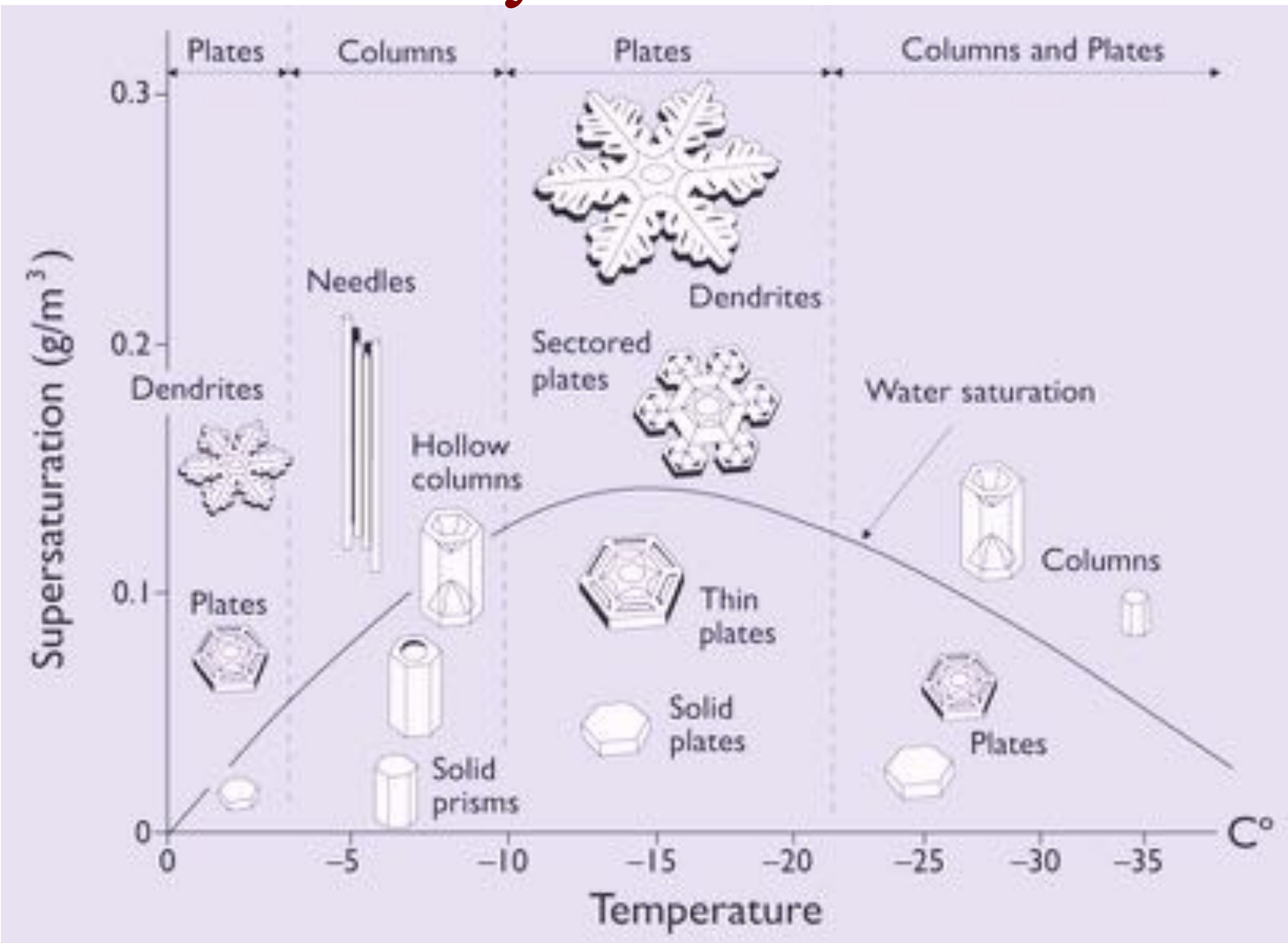
(http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm)

Ice-Crystal Axes and Crystal Forms



1. Structural arrangement of the principal types of snow crystals in relation to the crystal axes of ice. (After an illustration by Swiss Federal Institute for Snow and Avalanche Research)

Snow-crystal Classification



http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm

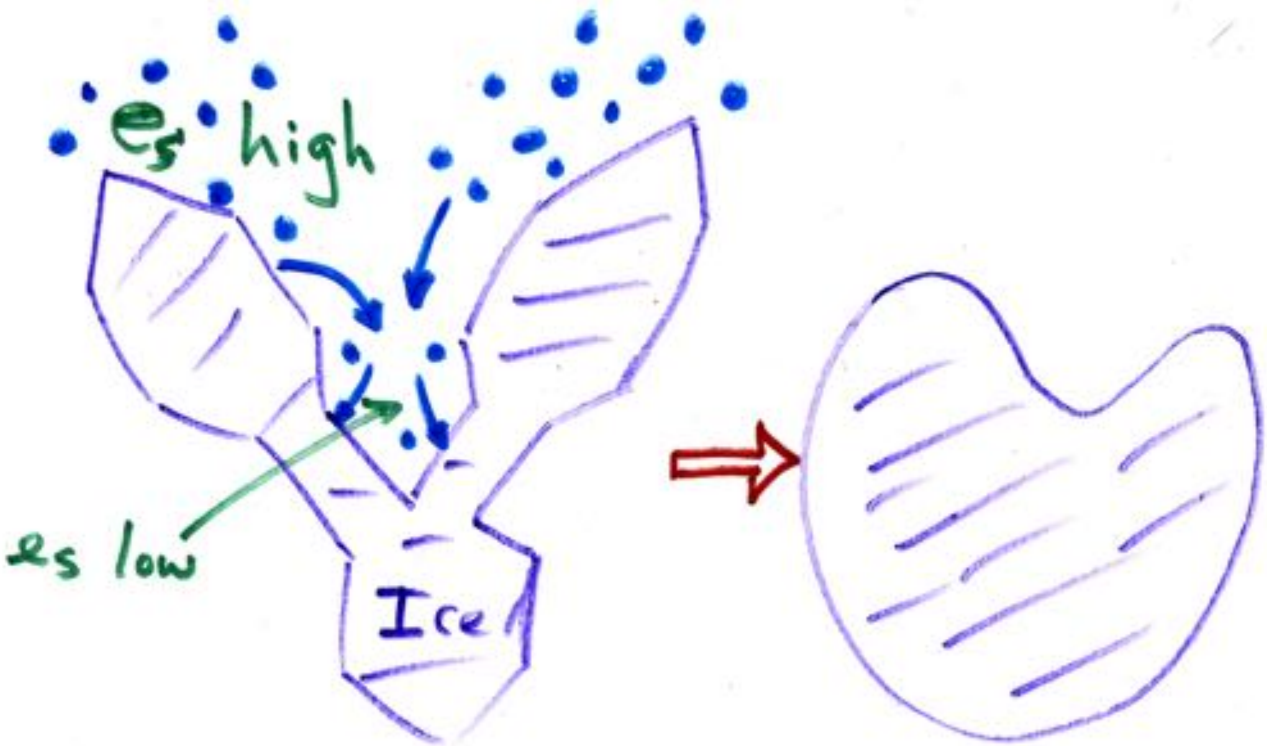
Dendrite

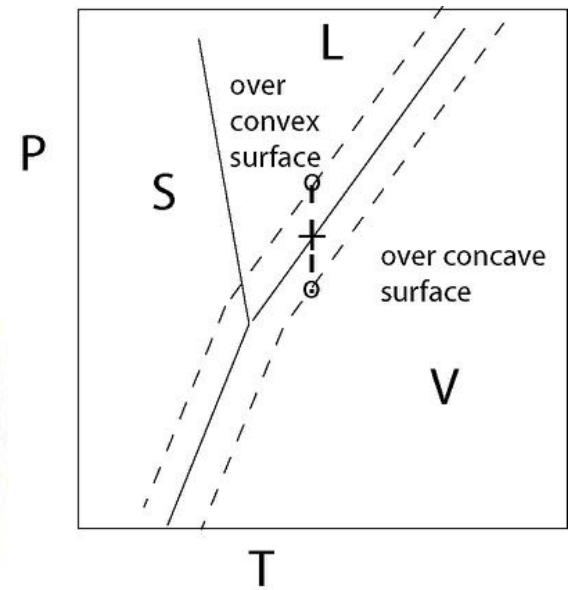
(http://radar.sci.hokudai.ac.jp/crystal/gallery.html)

Stellar Dendrite

(http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm)

Near-equilibrium Growth with Curvature





- e_s is high over convex surfaces and low over concave surfaces
- Vapor diffuses to concavities
- Crystal becomes more rounded over time

Fast Growth in Supersaturated Vapor

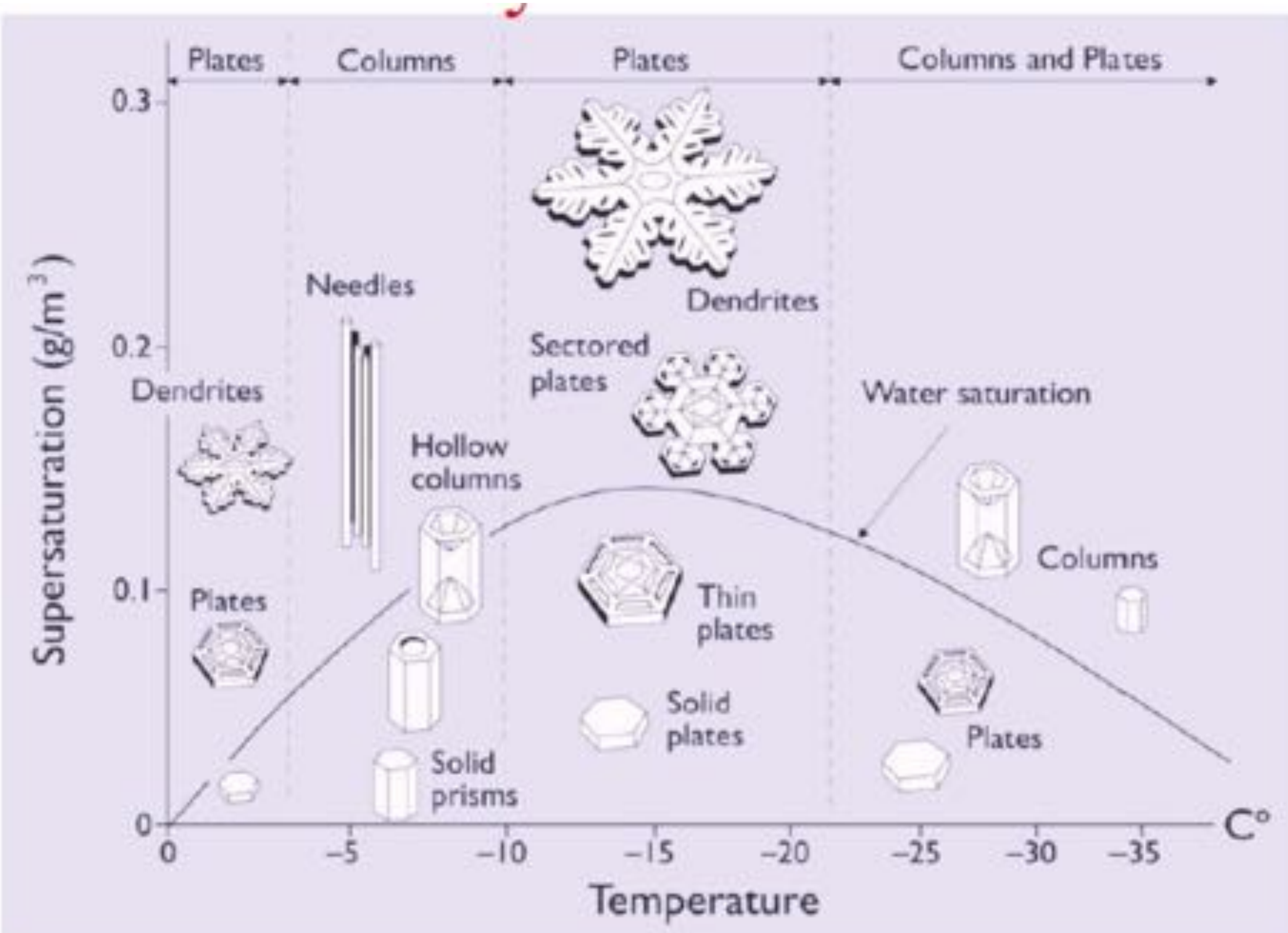
• Actual vapor pressure exceeds e_s everywhere on ice crystal.

• Crystal can establish $e_s(T)$ only in a boundary layer near crystal.

• External vapor is strongly attracted to the nearest ice surface.

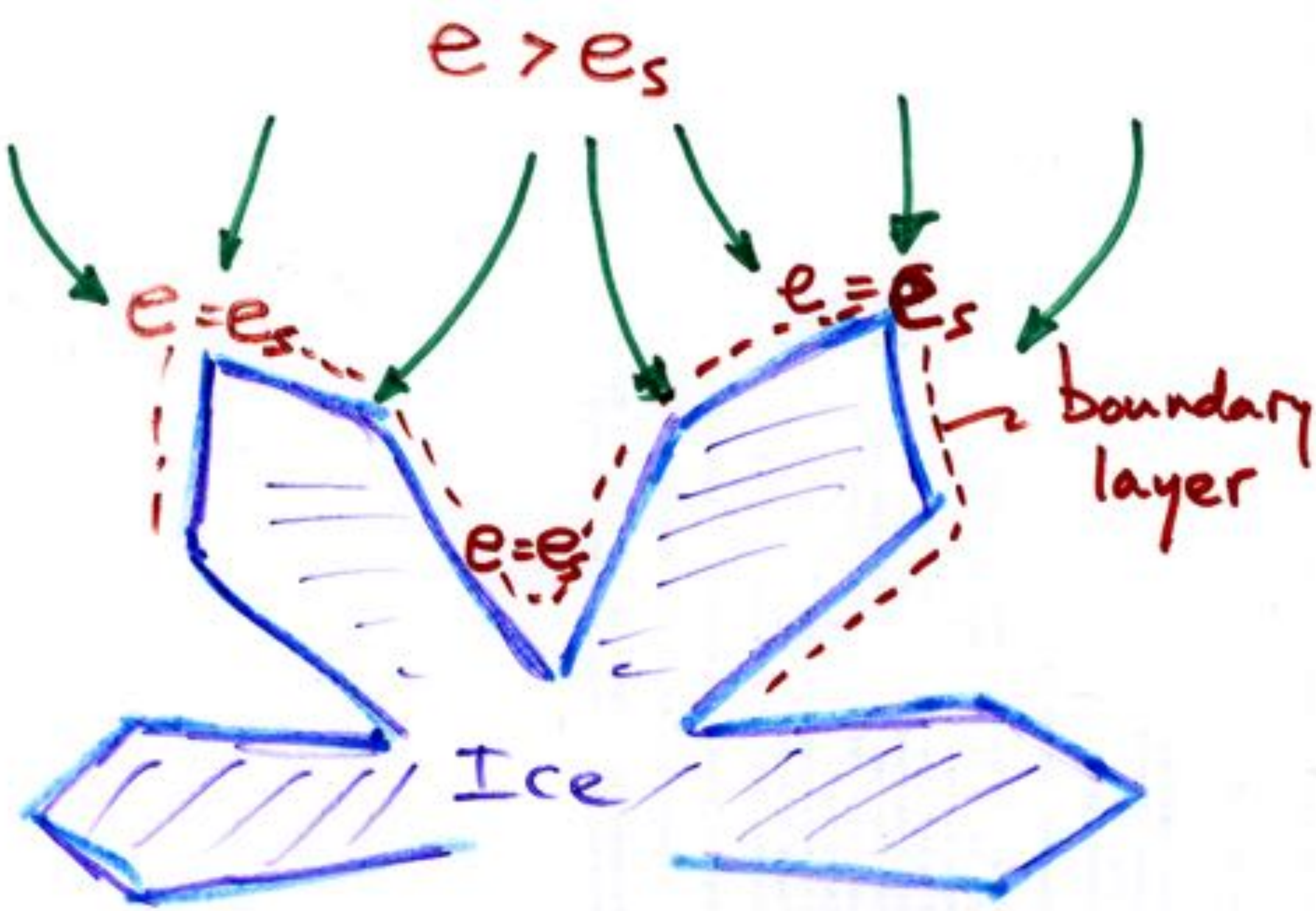
•As protuberances grow out into the vapor, they become more attractive deposition sites (positive feedback)

Snow-crystal Classification



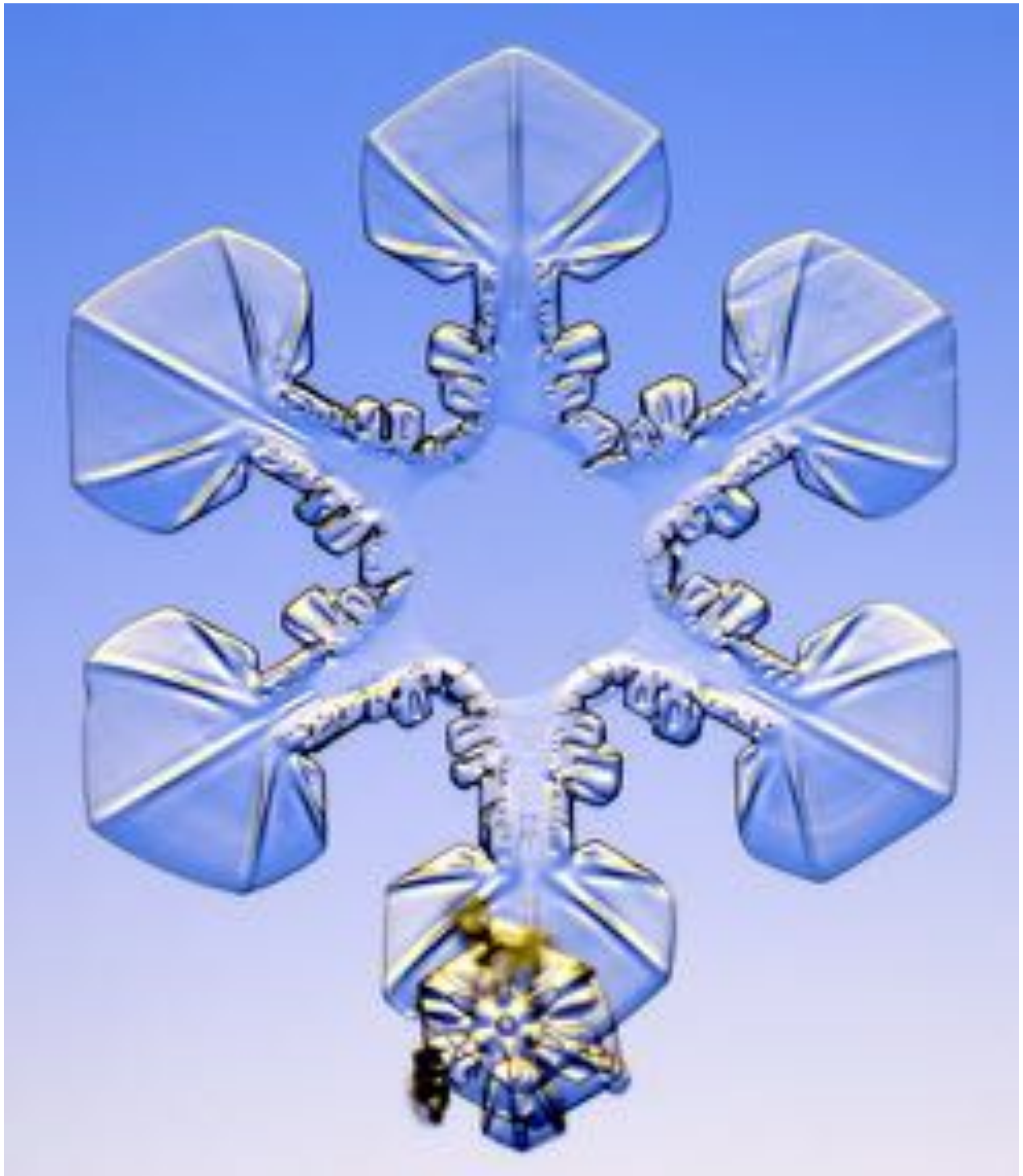
http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm

Fast Growth in Supersaturated Vapor



- Result is ***dendrites***

Dendritic Plate



(http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm)

Dendrites to Plates

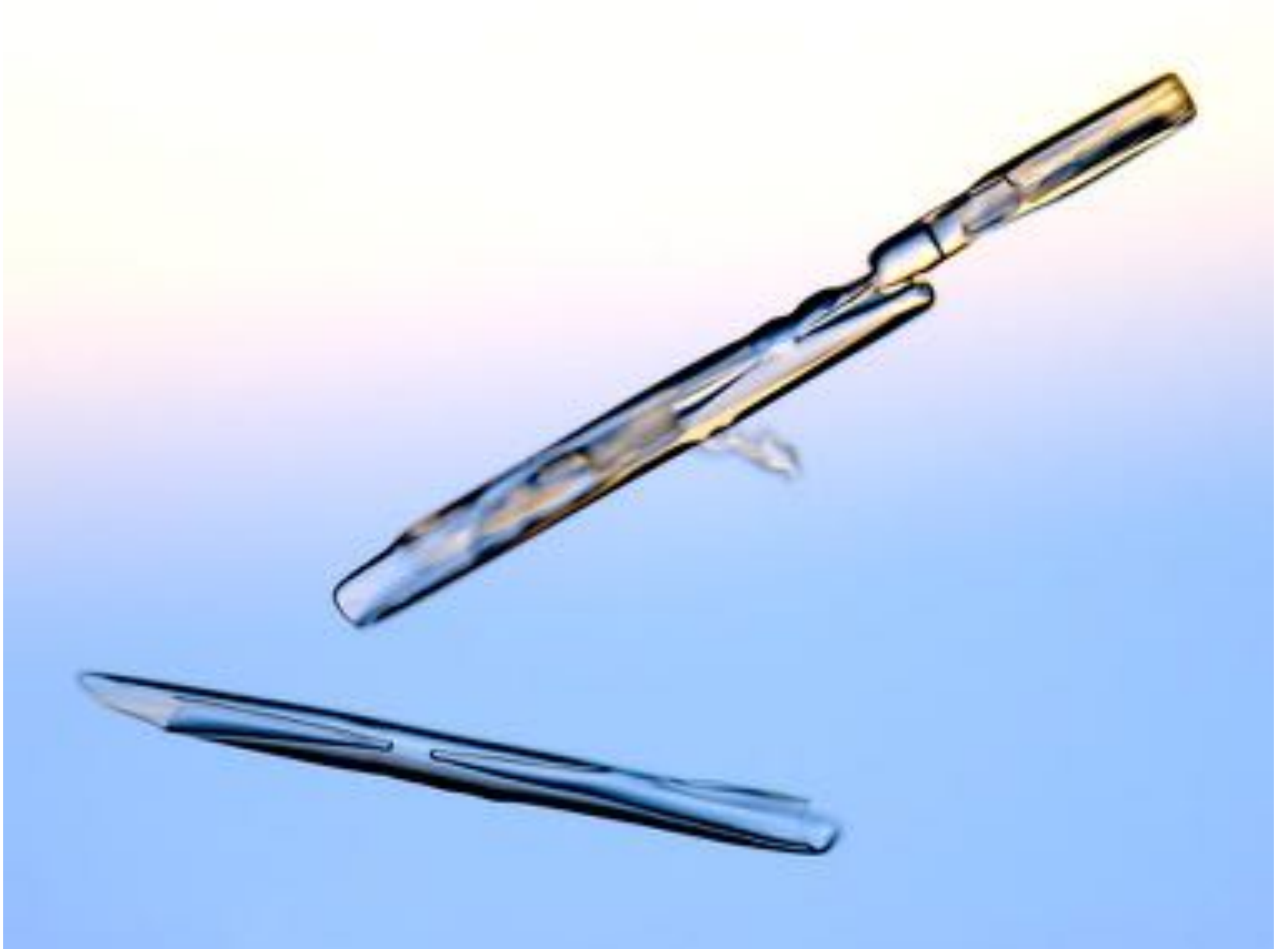
Capped Columns

http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm

Hollow Column

(http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm)

Ice Needles



(http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm)

Columns

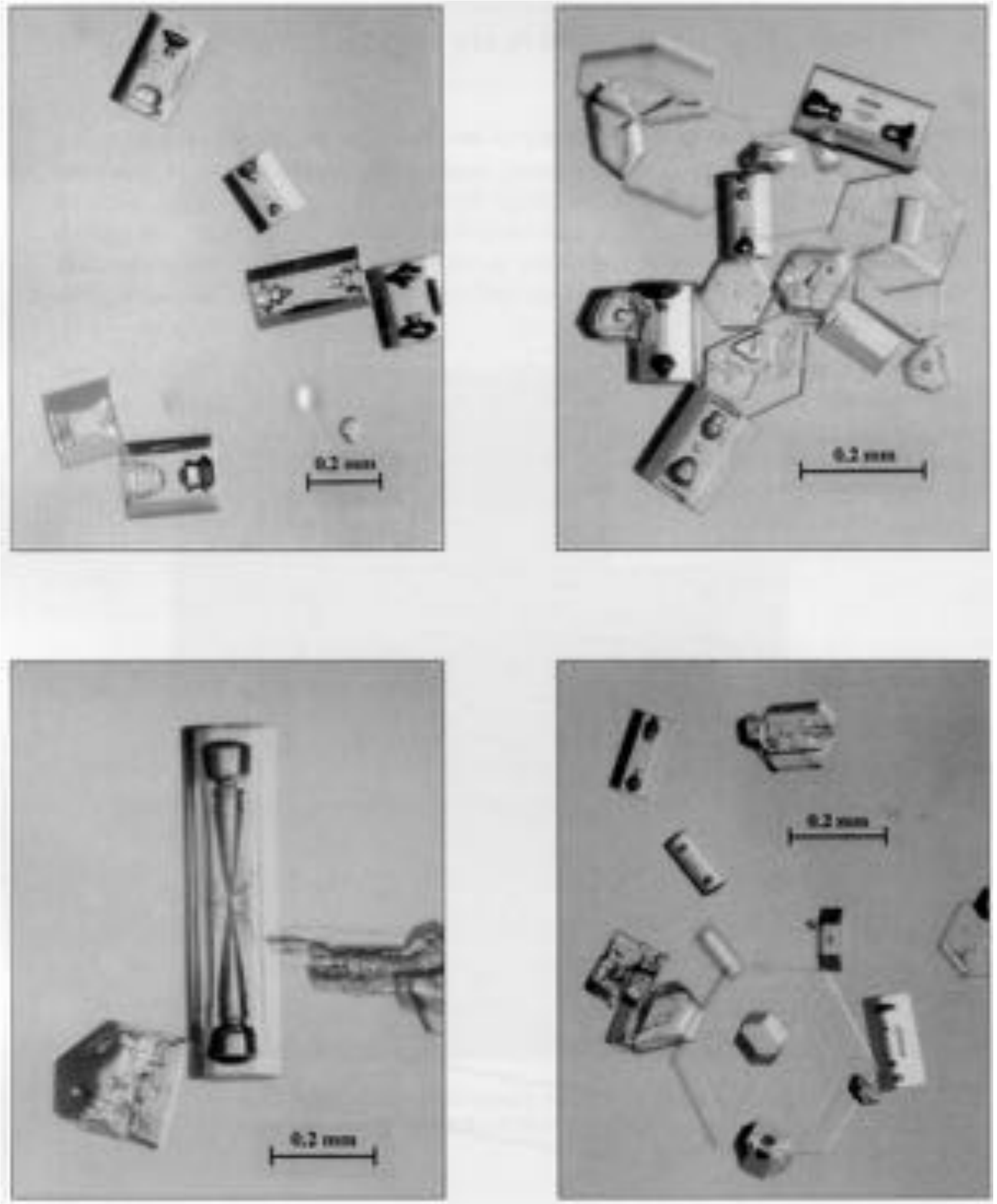
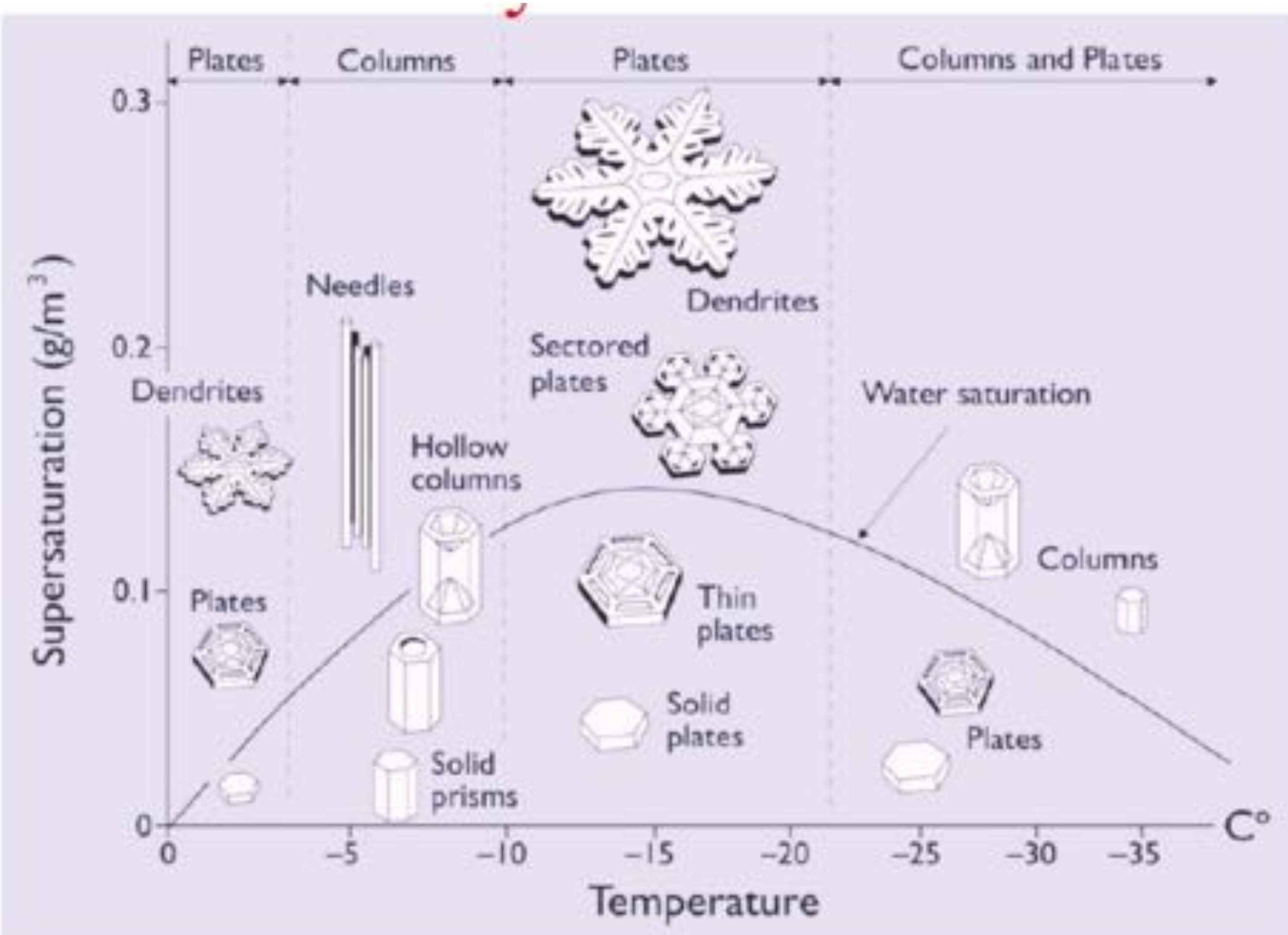


Figure 1-3. Some ice crystals that fell during halo displays. (Top left) Stubby columns. (Top right) Columns and plates. (Bottom left) Large column with beautiful internal structure. (Bottom right) Columns and plates.

(Walt Tape)

Snow-crystal Classification



http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm

Falling drops?

- Small drops are held aloft by turbulence

- When drops or crystals get larger than 40-50 μm, gravity wins

- How do snow crystals grow?

Saturation Vapor Pressure over Ice and Water

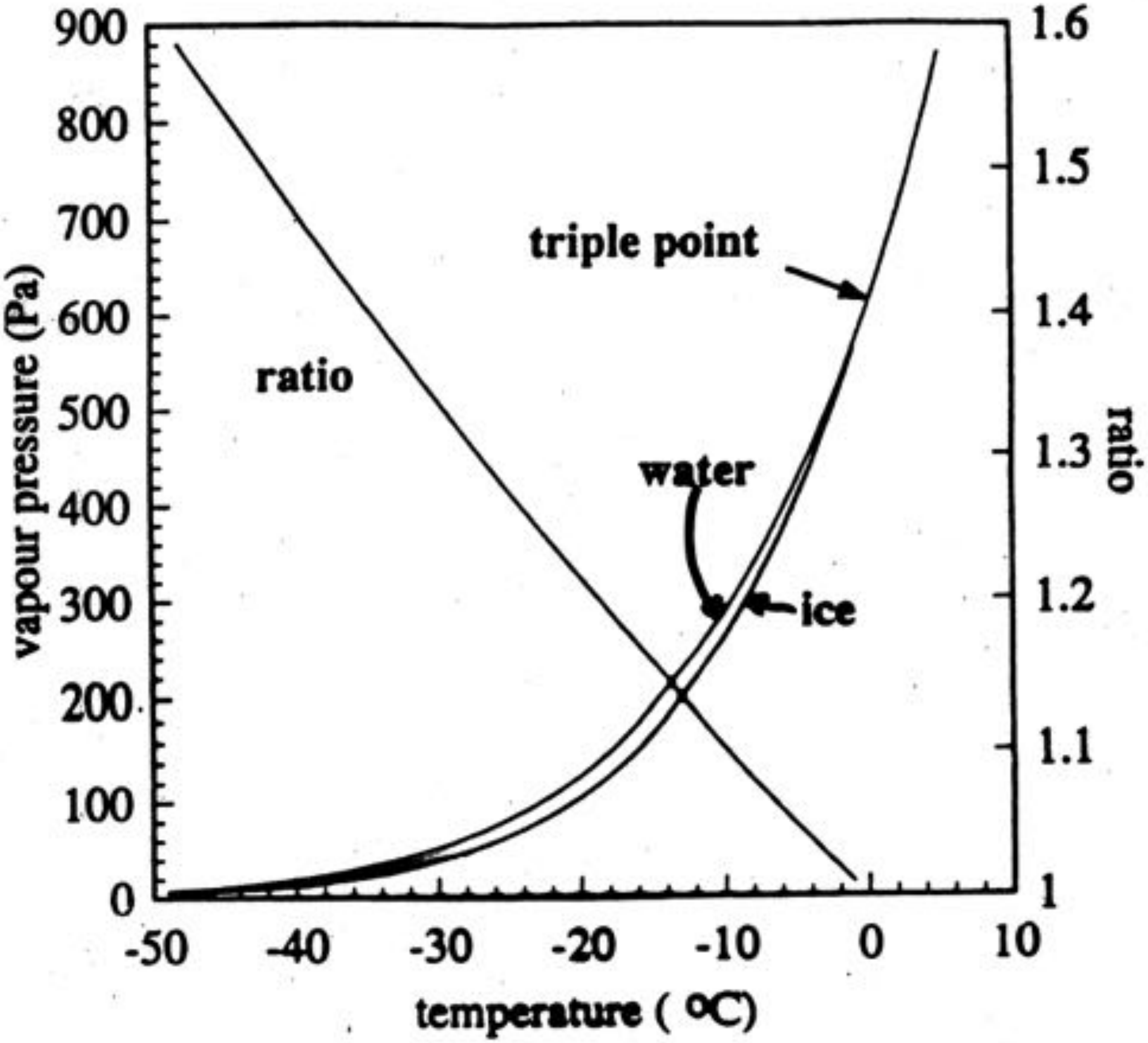
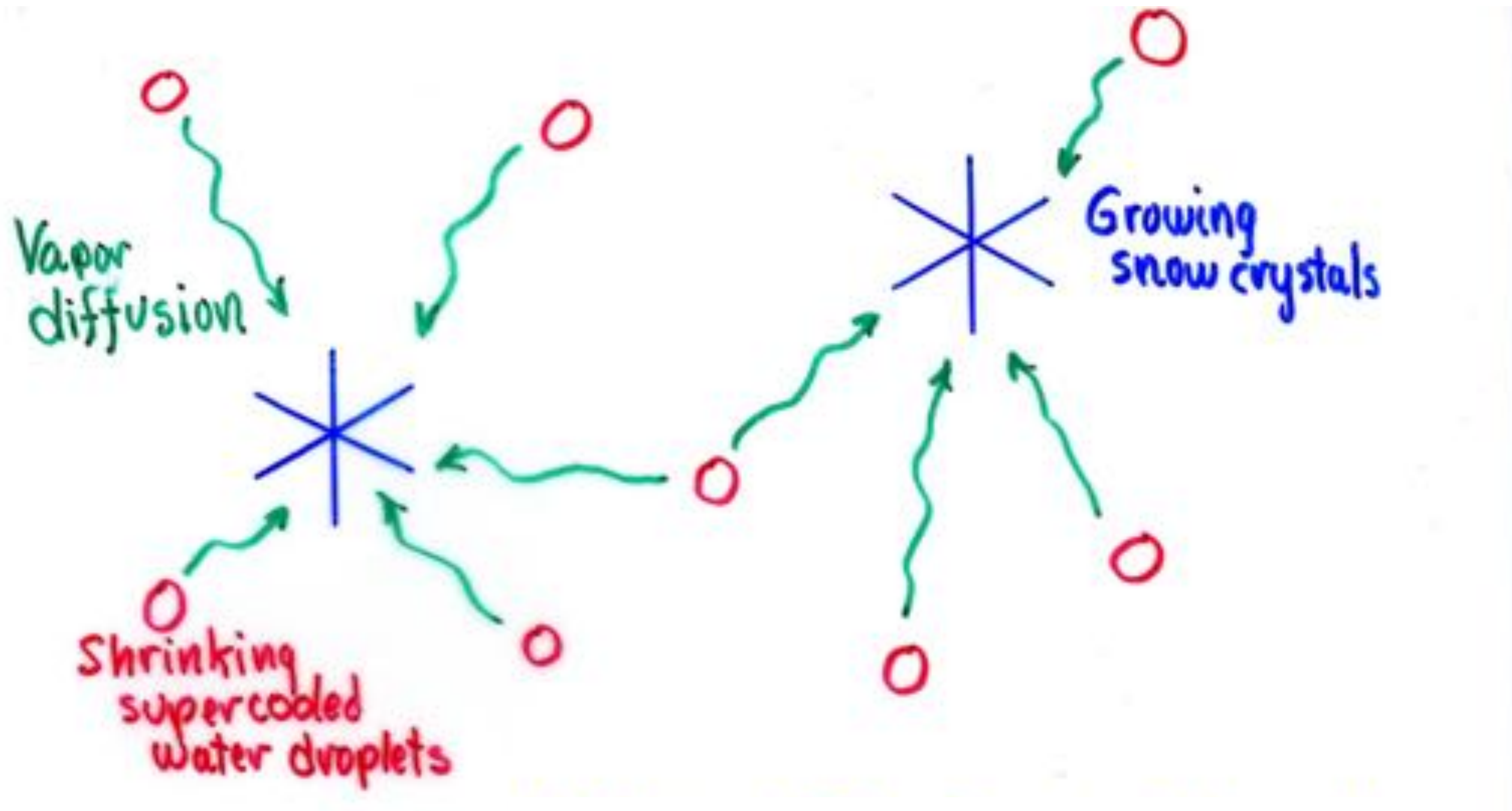


FIG. 1. Pressures of saturated water vapor with respect to water and ice, and their ratio.

A Mode of Snow Crystal Growth



(C.F. Raymond)

Riming

- Ice crystal becomes heavy enough to fall

- It collides with more supercooled droplets

- With ice lattice present, droplets freeze instantly (as long as falling ice crystal is cold enough to absorb the heat of fusion released as droplets freeze)

- The frozen droplets are called "rime"

Rimed Crystal

(http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm)

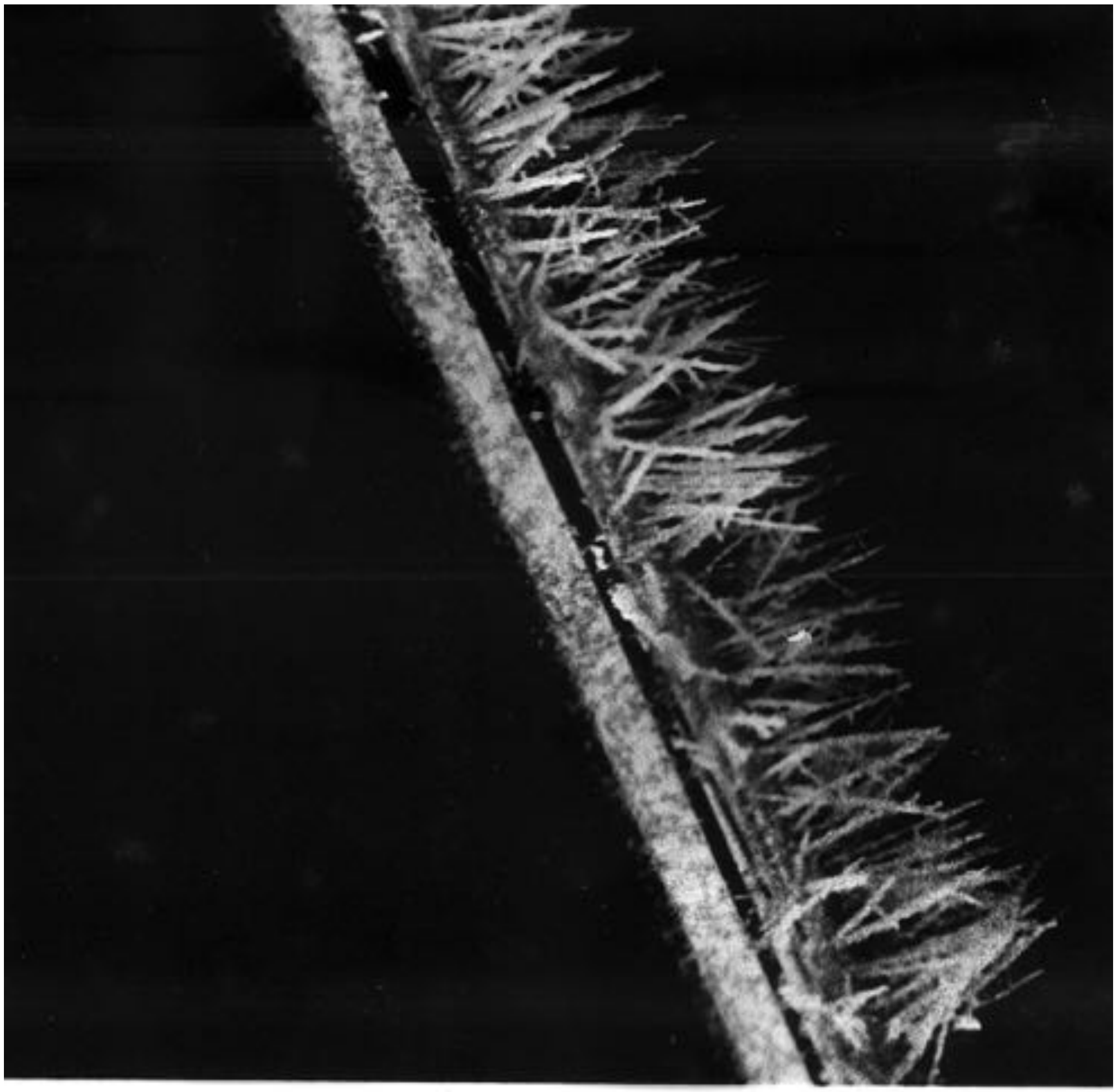
Rimed Trees – Hurricane Ridge

(Andy Radin http://www.fourfa.com/photo/Galleries/Canada/index.html)

Rimed Wires and Buildings

(CRREL Report 79-4)

Rimed Ski Pole



56. Rime spikes formed on a ski pole. 0.9X

Which way was the wind blowing?

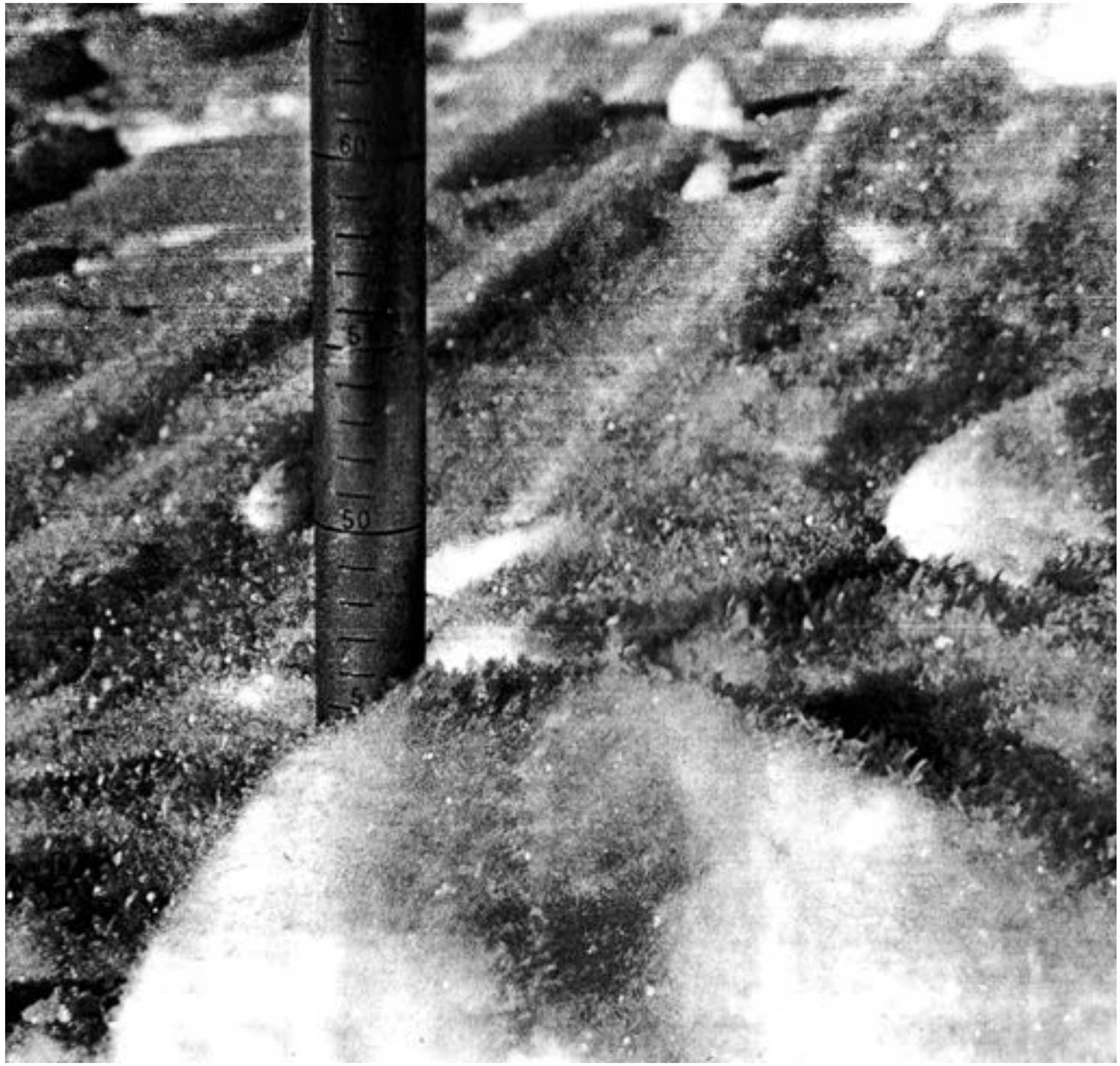
Why do you think so?

(CRREL Report 79-4)

Hoar Frost

- Ice deposited directly from super-saturated vapor.
- If snow is warm and air is cold, vapor pressure is higher in the snow than above
- Vapor diffusing upward becomes super-saturated
- It deposits as fragile delicate ice crystals

Hoar Frost on Snow Surface



(CRREL Report 79-4)