Cold Cloud Microphysics

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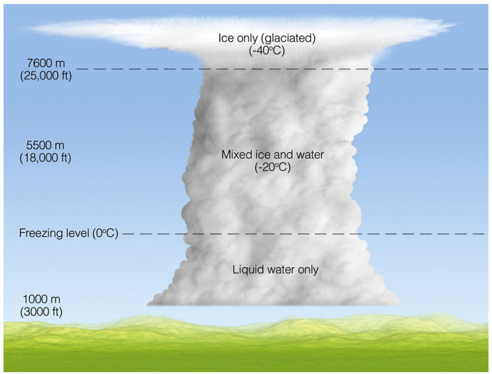
http://www.srh.weather.gov/mob/121103hole_punch/holepunch-main.html

Cold Cloud Microphysics



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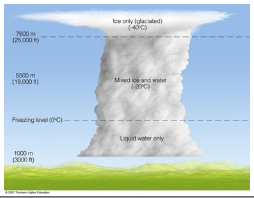
Cold Cloud Microphysics

- Cold clouds extend above the 0°C isotherm
- Supercooled droplets are present above 0°C
  - If a cloud contains both ice and supercooled droplets, then it is a mixed cloud
- Cold clouds composed entirely of ice crystals are glaciated



Nucleation of ice particles

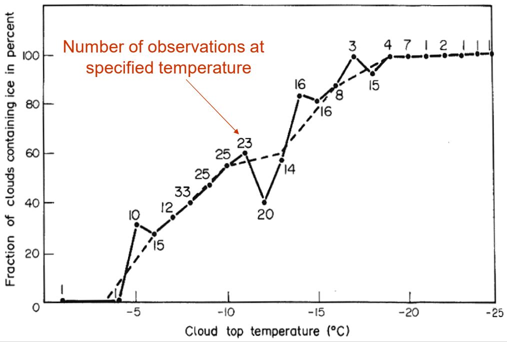
- A supercooled droplet can form an ice particle in one of two ways:
  - Homogeneous (spontaneous) nucleation
    - Ice embryo of critical size is formed by the chance aggregation of a sufficient number of water molecules in the droplet
  - Heterogeneous nucleation
    - Droplet contacts an ice nucleus (i.e., a *freezing* nucleus [inside], *contact* nucleus [by contact], or *deposition* nucleus [aids vapor to solid transition]) and freezes

Source: http://www.its.caltech.edu/~atomic/snowcrystals

Homogeneous nucleation

- Homogeneous nucleation of water molecules into ice embryos…
  - Occurs at about –36°C for droplets between 20 and 60 μm in radius
  - Occurs readily at about –39°C for larger droplets
  - Occurs only in high clouds (and infrequently)
- The presence of ice nuclei will increase the threshold temperature where ice will form

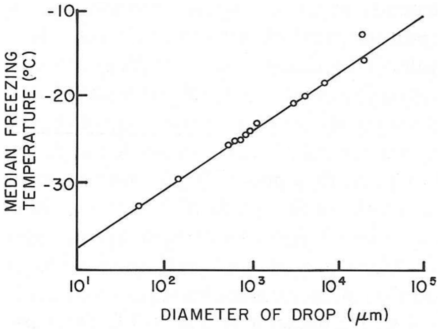
Fraction of clouds containing ice as a function of cloud top temperature



Heterogeneous nucleation

- Heterogeneous nucleation of water molecules into ice embryos…
  - Is aided by freezing nuclei
  - Allows an ice embryo to start off with the dimensions of the freezing nucleus
  - Occurs at much warmer temperatures than homogeneous nucleation

Heterogeneous nucleation



Median heterogeneous freezing temperatures for water drops as a function of their size (from a laboratory experiment)

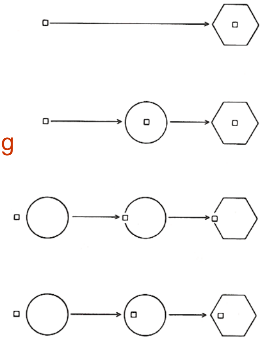
Ice Nuclei

Insoluble particles with a molecular structure similar to ice make good ice nuclei

Substance	Crystal lattice dimension		Temperature to nucleate ice (°C)	Comments
	a axis (Å)	*c* axis (Å)		
Pure substances				
Ice	4.52	7.36	0	—
AgI	4.58	7.49	−4	Insoluble
PbI_2	4.54	6.86	−6	Slightly soluble
CuS	3.80	16.43	−7	Insoluble
CuO	4.65	5.11	−7	Insoluble
HgI_2	4.36	12.34	−8	Insoluble
Ag_2S	4.20	9.50	−8	Insoluble
CdI_2	4.24	6.84	−12	Soluble
I_2	4.78	9.77	−12	Soluble
Minerals				
Vaterite	4.12	8.56	−7	
Kaolinite	5.16	7.38	−9	(Silicate)
Volcanic ash	—	—	−13	
Halloysite	5.16	10.1	−13	
Vermiculite	5.34	28.9	−15	
Cinnabar	4.14	9.49	−16	
Organic materials				
Testosterone	14.73	11.01	−2	
Chloresterol	14.0	37.8	−2	
Metaldehyde	—	—	−5	
β-Naphthol	8.09	17.8	−8.5	
Phloroglucinol	—	—	−9.4	
Bacterium *Pseudomonas* *Syringae*	—	—	−2.6	(Bacteria in leaf mold)

How might we use this information to modify the weather?

Ice nucleation mechanisms



Heterogeneous deposition

Condensation followed by freezing

Contact

Immersion

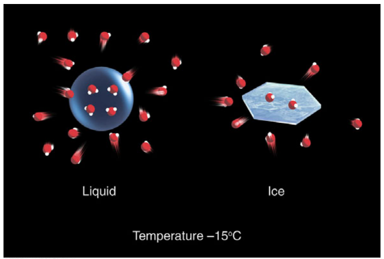
The different ways ice nuclei can account for ice formation

Ice multiplication (splintering)

- Supercooled droplet collides with an ice particle
- Droplet freezes in two stages:
  - Fine mesh of ice shoots through droplet
    - Freezes just enough water to raise the temperature of the droplet to 0°C
  - Droplet slowly transfers heat to the colder environment.
    - Ice shell forms on outside and freezes toward middle of drop.
    - Water gets trapped in the interior
    - Expanding interior ice causes the ice shell to crack and fragment
    - Ice splinters initiate new ice particles

Bergeron-Findeisen process

- Describes how ice crystals grow at the expense of supercooled water droplets in a water-saturated environment



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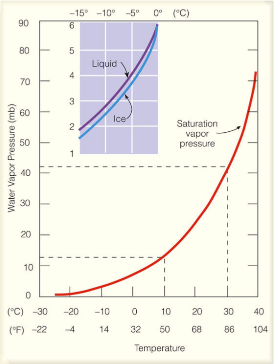
Bergeron-Findeisen process



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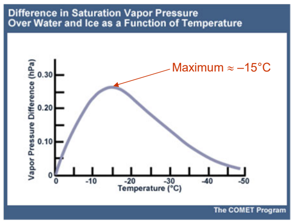
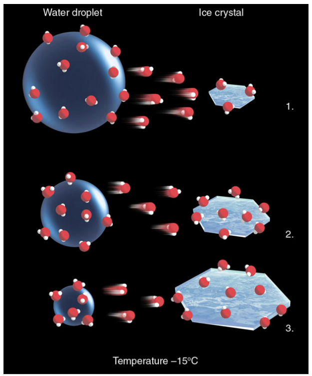


At the same subfreezing temperature, the saturation vapor pressure above a water surface is greater than that above an ice surface.

Ice crystal growth: Diffusion deposition



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The effect of phase differences

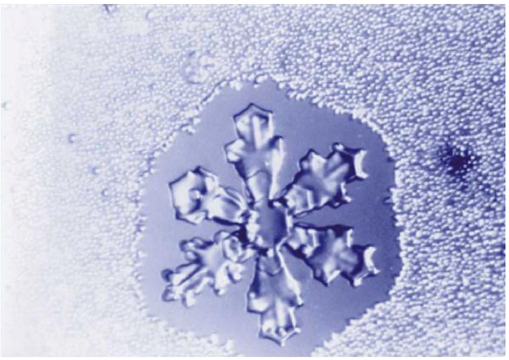
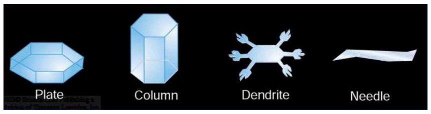


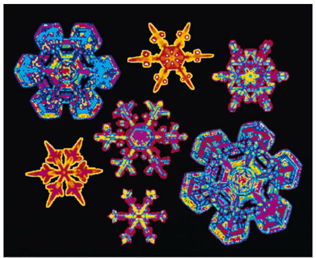
Photo: R. Pitter
Source: http://www.ems.psu.edu/~lno/Meteo437/Figures437.html

The effect of phase differences

http://www.srh.weather.gov/mob/121103hole_punch/holepunch-main.html

Ice crystal habits





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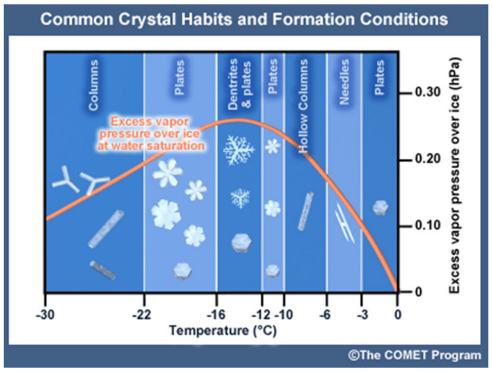
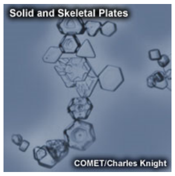
Snow crystals are always six-sided, but they come in an infinite variety of forms.

Ice crystal habits

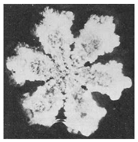


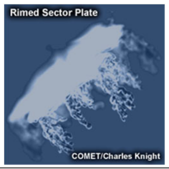
Ice crystal habits



Ice crystal growth: Accretion (riming)

- Ice crystals grow via collision with supercooled droplets
- Supercooled droplets freeze on contact to form rime ice
- Excessive riming results in the formation of graupel or snow pellets
- In convective storms, heavily rimed ice crystals can eventually produce hail





Ice crystal growth: Accretion (riming)

Derek Brown

Ice crystal growth: Accretion (riming)

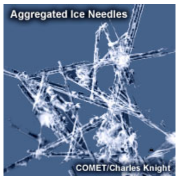
The top of Mount Washington in New Hampshire is coated in a rime ice, freezing moisture in the air.

Jim Cole / AP

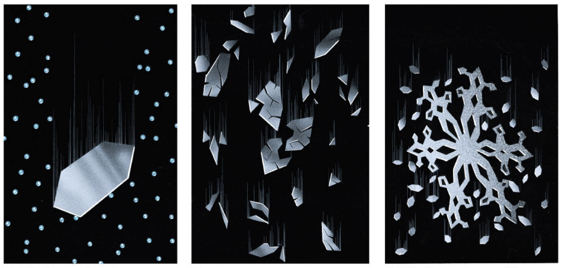
Derek Brown

Ice crystal growth: Aggregation

- Ice crystals can collide and stick together (aggregation)
- Liquid molecules on outer surface of crystals serve to increase bonding between colliding crystals
- Larger aggregations form in warmer regions → snowflakes
- Stickiness is maximized at or near 0°C



Ice crystal growth



(a) Falling ice crystals may freeze supercooled droplets on contact (accretion), producing larger ice particles.

(b) Falling ice particles may collide and fracture into many tiny (secondary) ice particles.

(c) Falling ice crystals may collide and stick to other ice crystals (aggregation), producing snowflakes.

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Accretion

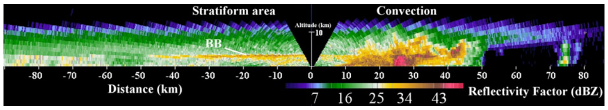
Aggregation

Formation of precipitation in cold clouds

- Deposition
  - By itself is not sufficiently rapid to produce large raindrops
- Riming and aggregation
  - Growth rate of an ice particle increases as the ice particle increases in size
- Growth of ice crystals, first by deposition from the vapor phase in mixed clouds and then by riming and/or aggregation, can produce precipitation-sized particles in reasonable time periods (~ 40 minutes)

Formation of precipitation in cold clouds

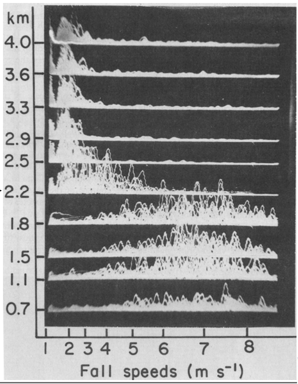
- The bright band (BB) in radar reflectivity corresponds to the melting level
  - In bright band, ice particles become coated with water, greatly increasing radar reflectivity Z (since Z α D^6 where D is drop diameter)
  - When ice particles melt, they turn into smaller droplets with much higher terminal velocities
  - Concentration of particles below bright band decreases



Radar cross-section of a squall line

Terminal velocities at various heights

Recall: the terminal fall speed of a particle is determined by a balance between the drag and the gravitational forces acting on the particle



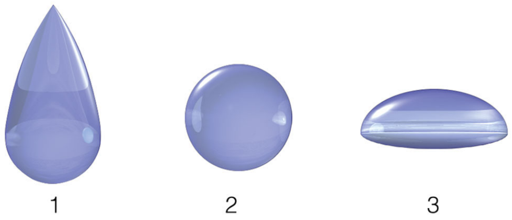
Frozen Precipitation

Melting Level

Liquid Precipitation

(Plot shows Doppler spectra)

What shape are raindrops?



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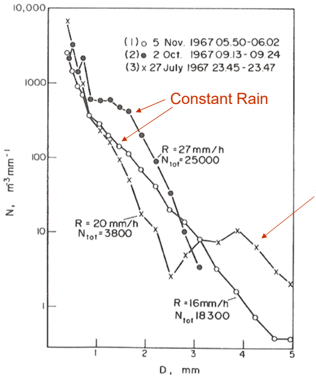
Observed drop size distributions



Constant Rain

Thunderstorm

Theoretical drop size distributions: Marshall–Palmer distribution*

- DSDs can be approximated by

$$N(D) = N_o e^{-\Lambda D}$$

N(D)dD = # of drops per unit volume with diameters between *D* and *D+dD*

$$\Lambda(R) = 41R^{-0.21}$$

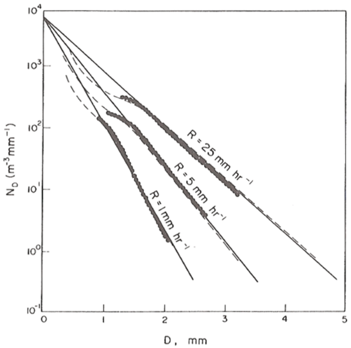
Λ = slope factor (cm^{-1})

R = rainfall rate (mm hr^{-1})

N_0 = 0.08 cm^{-4} = constant intercept parameter

*Based on a summer of observations in Canada in 1948

Observed and theoretical Marshall–Palmer DSDs



Dots: Observed (Marshall and Palmer 1948)
Lines: Best-fit exponential curves
Dashes: Observed (other authors)

Observed drop size distributions

Let’s see some actual drop size distributions from a single storm:

http://www.atms.unca.edu/cgodfrey/cimms/html/rain/