Cloud microphysics

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Overview of cloud physics lecture

- Atmospheric thermodynamics
  - gas laws, hydrostatic equation
  - 1st law of thermodynamics
  - moisture parameters
  - adiabatic / pseudoadiabatic processes
  - stability criteria / cloud formation
- Microphysics of warm clouds
  - nucleation of water vapor by condensation
  - growth of cloud droplets in warm clouds (condensation, fall speed of droplets, collection, coalescence)
  - formation of rain, stochastical coalescence
- Microphysics of cold clouds
  - homogeneous, heterogeneous, and contact nucleation
  - concentration of ice particles in clouds
  - crystal growth (from water phase, riming, aggregation)
  - formation of precipitation
- Observation of cloud microphysical properties
- Parameterization of clouds in climate and NWP models

Microphysics of cold clouds

- cold cloud: cloud that extends above 0°C level
- mixed cloud: clouds containing liquid droplets and ice crystals
- glaciated cloud: pure ice cloud

Homogeneous nucleation

- water droplets become super-cooled when air parcel ascends and cools down
- homogeneous nucleation: pure water droplet freezes
  phase transition: liquid ⇒solid
- process analogue to nucleation of liquid droplet from vapor phase

Homogeneous and heterogeneous nucleation

- measured median freezing temperatures
- homogeneous freezing
- heterogeneous freezing

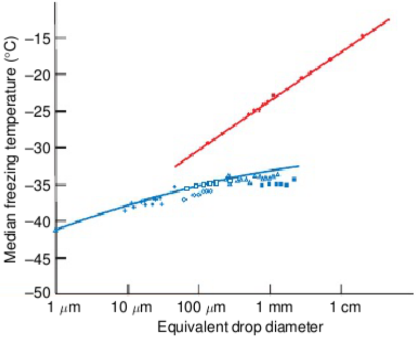

Fig. 6.29 Median freezing temperatures of water samples as a function of their equivalent drop diameter. The different symbols are results from different workers. The red symbols and red line represent heterogeneous freezing, and the blue symbols and line represent homogeneous freezing. [Adapted from B. J. Mason, *The Physics of Clouds*, Oxford Univ. Press, Oxford, 1971, p. 160. By permission of Oxford University Press.]

Figure from Wallace and Hobbs

Heterogeneous nucleation

- water molecules in droplet collect onto surface of particle contained in droplet (freezing nucleus) ⇒ice like structure is formed ⇒growth starts at larger crystal size ⇒freezing occurs
- heterogeneous nucleation occurs at much higher T than homogeneous nucleation

Further nucleation processes

Contact nucleation

Freezing starts when suitable particle (contact nucleus) comes into contact with super-cooled droplet.

Deposition

Some particles (deposition nuclei) serve as centers where ice forms directly from vapor phase. Conditions: air supersaturated w.r.t. ice and T sufficiently low

When air is supersaturated w.r.t. ice and water, some particles may act as freezing nucleus (vapor ⇒liquid ⇒ice) or as deposition nucleus (vapor ⇒ice).

Effective ice nuclei

- crystallographic arrangements similar to ice (hexagonal structure)
- insoluble in water
- inorganic soil particles (e.g. clay) can nucleate at T>-15°C most snow crystals found on ground contain clay mineral particles
- AgI is often used for cloud modification

Ice nucleating crystals

crystal substance	lattice constants [Å] a	b	reported nucleation threshold [°C]
Ice	4.52	7.37	
AgI	4.58	7.49	-4
PbI_2	4.54	6.86	-6

Table: adapted from Byers, Elements of cloud physics

AgI and PbI_2 have hexagonal structures and are insoluble in water

The lattice structure is very similar to ice ⇒AgI and PbI_2 are active nucleation agents for ice crystals

Onset of ice nucleation

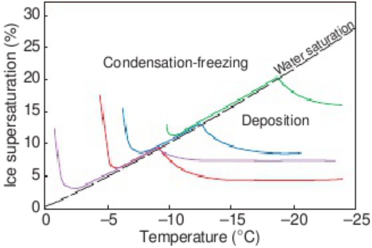

Fig. 6.30 Onset of ice nucleation as a function of temperature and supersaturation for various compounds. Conditions for condensation-freezing and ice deposition are indicated. Ice nucleation starts above the indicated lines. The materials are silver iodide (red), lead iodide (blue), metaldehyde (violet), and kaolinite (green). [Adapted from *J. Atmos. Sci.* **36**, 1797 (1979).]

Figure from Wallace and Hobbs

- Onset of of ice nucleation as function of temperature and supersaturation
- Onset occurs at higher T under water-supersaturated conditions
- Lower T required under water-subsaturated conditions, when only deposition is possible

Preactivation

- particle serves as ice nucleus ⇒most of the ice evaporates (particle becomes not warmer than -5°C, $RH_i > 35\%$) ⇒then particle can serve as ice nucleus a little higher T
- Example: ice particles from upper level clouds that evaporate before reaching the cloud bottom may leave behind preactivated ice nuclei.

Measurement of active ice nuclei

- measurement principle: draw a known volume of air into container ⇒measure number of ice crystals at T
    - expansion chambers: cooling is achieved by first compressing the air and then suddenly expanding it
    - mixing chambers: cooling is achieved by refrigeration at constant V
- counting number of particles N:
    - illumination of certain volume in chamber ⇒visually estimate N
    - let ice crystals fall into dish of super-cooled salt or sugar solution ⇒crystals grow and can be counted
    - let ice crystals pass through capillary tube where they produce audible clicks that can be counted

Measurements of ice nucleus concentrations

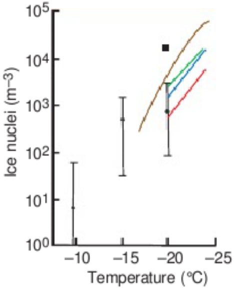

Fig. 6.31 Measurements of average ice nucleus concentrations at close to water saturation in the northern and southern hemispheres. Southern hemisphere, expansion chamber (red); southern hemisphere, mixing chamber (blue); northern hemisphere, expansion chamber (green); northern hemisphere, mixing chamber (black square); Antarctica, mixing chamber (brown). Vertical lines show the range and mean values (dots) of ice nucleus concentrations based on Millipore filter measurements in many locations around the world.

Figure from Wallace and Hobbs

Empirical relationship

$$\ln N = a(T - T_1)$$

T_1 – temperature at which 1 nucleus/liter is active (typically ≈ 20°C)
a – constant between 0.3 and 0.6, depending on conditions

e.g. a=0.6 ⇒N increases by factor of 10 for every 4°decrease in T

Heterogeneous nucleation

- measured median freezing temperatures
- homogeneous freezing
- heterogeneous freezing: increase with R mainly due to increasing probability that droplet contains freezing nucleus

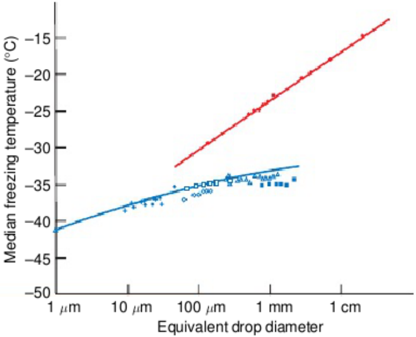

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Figure from Wallace and Hobbs

Concentration of active ice nuclei

Only small amount of aerosols act as ice nuclei.

urban air: aerosol concentration $\approx 10^8$/l $\Rightarrow$only 1 acts as ice nucleus at -20°C.

Effect of supersaturation on ice nucleus concentration

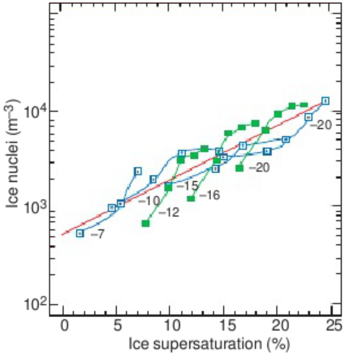


Fig. 6.32 Ice nucleus concentration measurements versus ice supersaturation; temperatures are noted alongside each line. The red line is Eq. (6.35). [Data reprinted from D. C. Rogers, "Measurements of natural ice nuclei with a continuous flow diffusion chamber," *Atmos. Res.* **29**, 209 (1993) with permission from Elsevier—blue squares, and R. Al-Naimi and C. P. R. Saunders, "Measurements of natural deposition and condensation-freezing ice nuclei with a continuous flow chamber," *Atmos. Environ.* **19**

The greater the supersaturation the more particles act as ice nuclei.

empirical fit:

$$N = \exp(a + b(100(S_i - 1)))$$

a=-0.639, b=0.1296

Concentration of ice particles in clouds

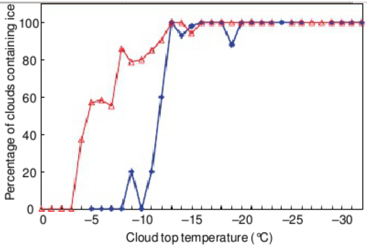


Fig. 6.33 Percentage of clouds containing ice particle concentrations greater than about 1 per liter as a function of cloud top temperature. Note that on the abscissa temperatures decrease to the right. Blue curve: continental cumuliform clouds with base temperatures of 8 to −18 °C containing no drizzle or raindrops prior to the formation of ice. [Data from *Quart. J. Roy. Met. Soc.* **120**, 573 (1994).] Red curve: clean marine cumuliform clouds and clean arctic stratiform clouds with base temperatures from 25 to −3 °C containing drizzle or raindrops prior to the formation of ice. [Based on data from *Quart. J. Roy. Met. Soc.* **117**, 207 (1991); A. L. Rangno and P. V. Hobbs, "Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations," *J. Geophys. Res.* **106**, 15,066 (2001) Copyright

Figure from Wallace and Hobbs

- When drizzle or raindrops are present prior to formation of ice, clouds freeze at higher T compared to clouds without drizzle/raindrops.

- T<-13°C ⇒100% of clouds contain ice
- 0°C>T>-8°C ⇒clouds generally consist of super-cooled droplets

Maximum concentration of ice particles

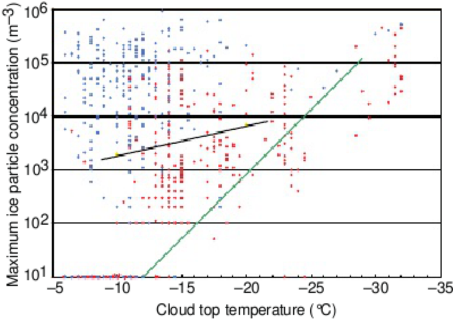


Fig. 6.34 Maximum concentrations of ice particles versus cloud top temperature in mature and aging marine cumuliform clouds (blue dots) and in continental cumuliform clouds (red dots). Note that on the abscissa temperatures decrease to the right. Symbols along the abscissa indicate ice concentrations ≤ 1 liter^{-1}, which was the lower limit of detection. The green line shows ice nucleus concentrations predicted by Eq. (6.33) with $a = 0.6$ and $T_1 = 253$ K. The black line shows ice nucleus concentrations from (6.35) assuming water-saturated conditions. [Data from *J. Atmos. Sci.* **42**, 2528 (1985); and *Quart. J. Roy. Met. Soc.* **117**, 207 (1991) and **120**, 573 (1994). Repro-

- empirical relation from laboratory measurements corresponds to minimum values of maximum concentrations
- concentrations in natural clouds can be several orders of magnitude larger !

Explanations for high ice crystal concentrations

- measurement techniques in laboratory can not be applied to natural clouds (conditions too different)
- ice multiplication or ice enhancement process
    - some crystals are fragile and may break up in several splinters when colliding with other particles
    - Super-cooled droplet freezes in isolation (e.g. free fall), or after it collides with an ice particle (i.e. riming – freezing of droplet on ice crystal) ⇒freezing in 2 stages, particle may explode in 2nd stage of freezing

Stages of freezing

1. fine mesh of ice shoots through droplet and freezes just enough water to enhance temperature to 0°C (happens almost instantaneously)
2. 2nd stags of freezing much slower, heat is transferred from partially frozen droplet to colder ambient air
    - ice shell forms over surface of droplet and thickens progressively inward
    - water is trapped in interior ⇒expands as it freezes ⇒large stresses on ice shell
    - finally ice shall cracks or even explode ⇒numerous small ice particles

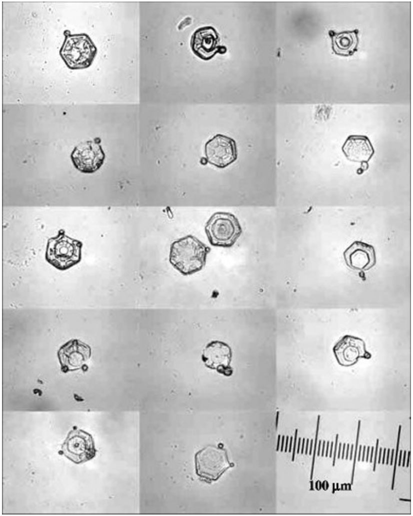
Riming

Riming

Freezing of droplet on ice crystal.

- riming might be most important for ice enhancement
- when ice particle falls through super-cooled cloud it is impacted by thousands of droplets, each may shed numerous ice splinters
- Laboratory measurement
  - Setup:
    - droplet concentration: 50/cm^3
    - droplet diameter: 5–35μm
    - liquid water content: 0.2 g/m^3
    - temperature: -4.5°C
    - impact speed: 3.6 m/s
  - 300 splinters are produced for every μg of accumulated rime

Riming



from Avila et al., 2009

Observation of ice crystal concentrations in clouds

- high concentrations of ice particles mainly found in older clouds
- young ($<$10 min) cumulus towers consist entirely of water droplets,
  after 10 min ice particles form rapidly
- high concentrations occur after formation of drops $> 25\mu$m and when rimed particles occur
  $\Rightarrow$consistent with hypothesis that riming is reason for high ice particle concentrations
- BUT: Riming process observed in laboratory much slower as in natural clouds, where an explosive formation of extremely high concentrations is observed
- Explosive formation of ice crystals not yet understood!

Ice development in small cumuliform clouds

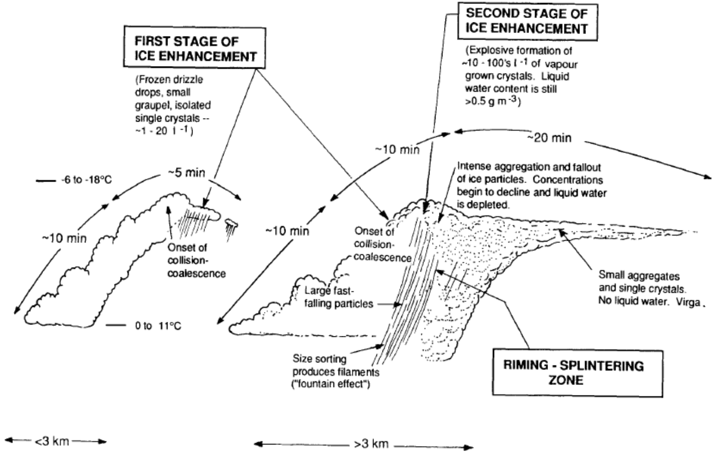


Figure 14. Schematic of observations and speculations presented in this paper on the formation of high ice particle concentrations in small polar maritime cumuliform clouds. The clouds on the right and left represent those indicated by A and B in Fig. 1.

from Rangno and Hobbs (1991)