Lecture 3. Impacts of aerosols on clouds/precipitation in the Arctic: In-search for observational evidence.

Background materials: *Arctic climate, aerosol and clouds*

Required reading:

Girard, E., Jean-Pierre Blanche, and Y. Dubois, Effects of arctic sulphuric acid aerosols on wintertime low-level atmospheric ice crystals, humidity and temperature at Alert, Nunavut. Atmospheric Research 73, Issues 1-2, 2005.

Garrett, T. J. and C. Zhao, Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. Nature, 440, 10.1038/nature04636, 787-789, 2006.

Recommended reading (for Lectures 3-4):

Quinn, P. K., Shaw, G., Andrews, E., Dutton, E. G., Ruoho-Airola, T., and Gong, S. L.: Arctic. Haze: Current trends and knowledge gaps. Tellus, 59B, 99–114, 2007.

Law, K.S., and A. Stohl, Arctic Air Pollution: Origins and Impacts. Science *315. no. 5818, pp. 1537 – 1540, 2007.*

Arctic climate

- Because of the high latitude, there is a strong seasonal cycle and a weak diurnal cycle. Annual mean incoming solar radiation north of the Arctic Circle is 100 W/m^2, most of it between the spring and autumn equinoxes. Daily mean temperatures are below freezing for several months. The daily temperature range is small because of the level Sun, i.e. less than 3 K, except in April and May when they may approach 6 K.
- On average, the annual precipitation in the Arctic is less than 500 mm, typically between 200 and 400 mm. Cold air can hold less moisture than warmer air, and although the frequency of precipitation may be high, the overall intensity is low. This explains why the accumulation of snow is relatively low in winter in much of the Arctic.
- The generally open landscape of the Arctic region means that winds are not greatly slowed by friction at ground level. Wind is an important factor in snow distribution, causing scouring in exposed areas and deposition in sheltered locations. It also augments the chilling effect of low temperatures. Wind also affects sea surface stability, increases mixing in the water column, and it influences ice drift.

Arctic climate trends (observed and predicted):

- Increasing temperature. T have increased in recent decades over most of the region, especially in winter. GCMs models project further increase in T.
- Rising river flows. River discharge to the ocean has increased over much of the Arctic.
- Declining snow cover. Snow cover extent has declined about 10% over past 30 years, with the greatest decline in spring
- Increasing precipitation. Arctic precip has increased by about 8% over past century. Much of the increase has come as rain, mainly in fall and winter.
- Diminishing lake and river ice. The strongest trends are over North America and western Eurasia.

- Cloud fraction has decreased during the Arctic winter and increased in spring and summer.

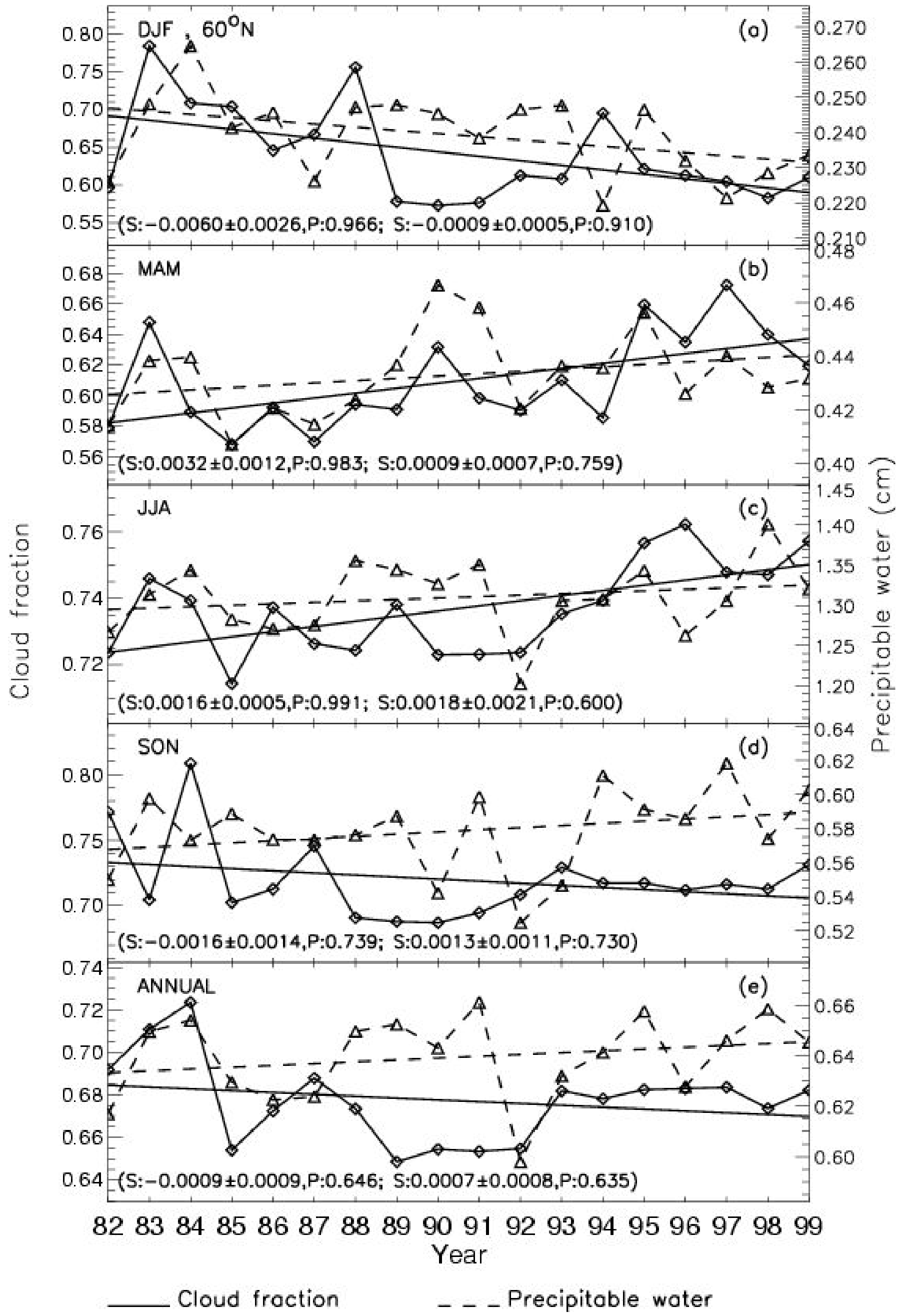
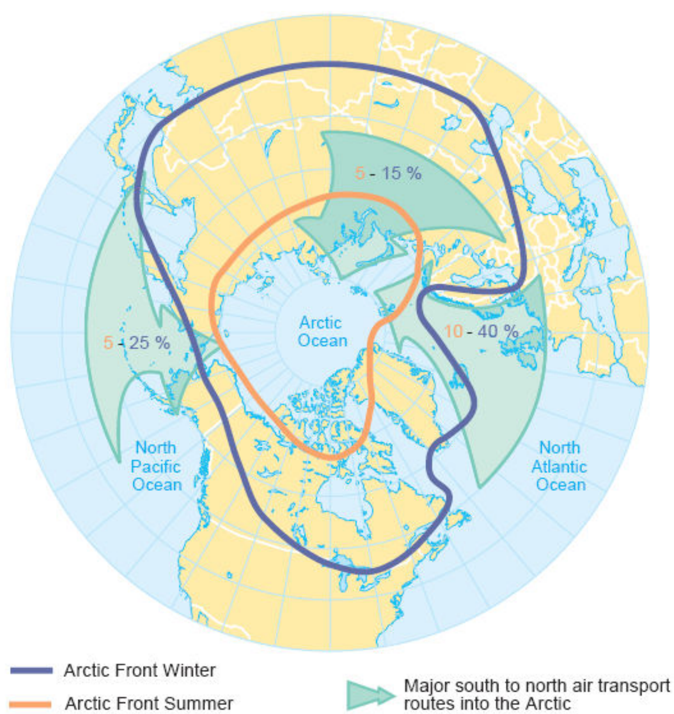


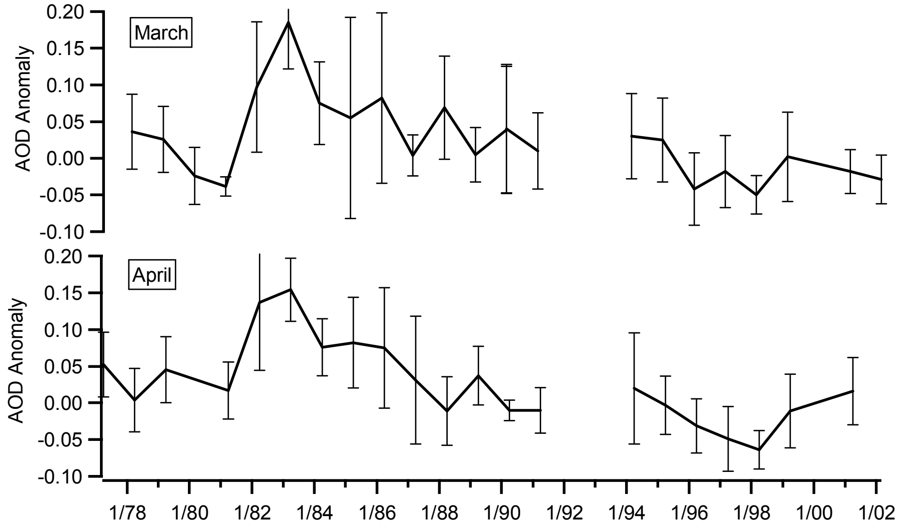
Figure shows Time series and trends in cloud fraction and precipitable water (based on satellite data) in winter (DJF), spring (MAM), summer (JJA) and autumn (SON) over the area north of 60oN. The numbers in parentheses are the slope of the trend with its uncertainty and F test confidence level, where S stands for slope per year and P for confidence level for that slope. The first group of S and P denotes the cloud fraction trend (solid line); the second group denotes the precipitable water (dashed line) (From *Key et al.)*

Arctic aerosols

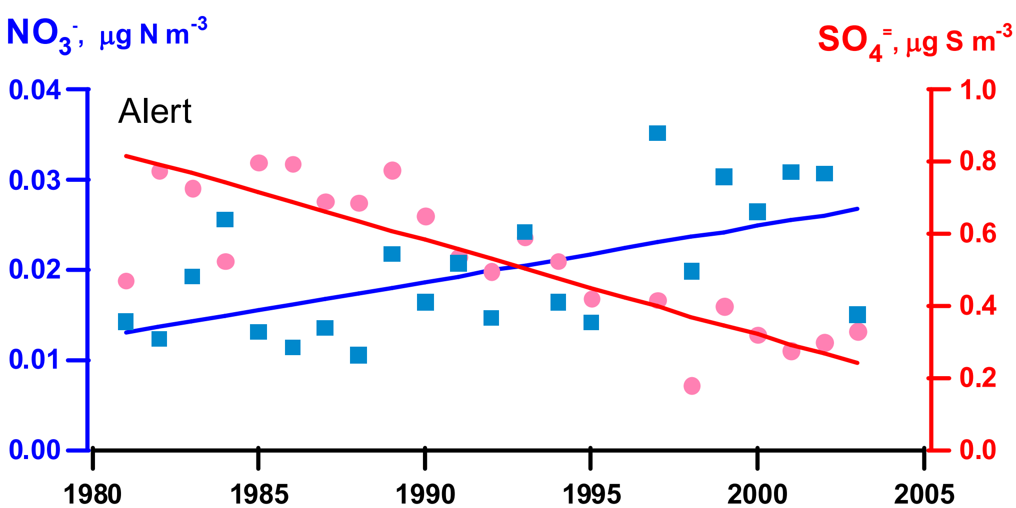
- Local sources vs. long-range transported aerosols
- The term "Arctic haze" was introduced in 1950s referring to layers of aerosol forming haze which obscured visibility. The nature of Arctic haze is long-range transposed aerosols.
- Arctic haze is a seasonal phenomenon: maximum in Spring, accumulated over the winter time because of slow removal processes. During the polar night, there is strong temperature inversion that stabilizes the atmosphere. It inhibits turbulent transfer, formation of clouds and precipitation (hence aerosol removal processes are weak). In addition, transport from the mid-latitudes to the Arctic intensifies during the winter and spring. The Arctic haze layers are highly inhomogeneous vertically (meters to 1 km thick) and horizontally (20 to 200 km). The Arctic haze occurs primarily in the lowest 5 km, peaking in the lowest 2. High-altitude, long-range transport forms aerosol layers high (up to 8 km), for instance transport of Asian dust.



- Observations of aerosol optical depth (AOD) at Barrow, Alaska. Shown are Monthly Averaged AOD Anomalies at Barrow: 1976 – 2002 (relative to a base of non-volcanic years). Volcanic effects in the stratosphere have been removed. Note a decreasing trend!



- Different aerosol species show different trends. Example of sulfates and nitrates. Data are for Alert. Sources of nitrates are diesel and gasoline engines, fertilizer. Sources of sulfates are fossil full burning (e.g., coal). Trends depend on location and time.



Arctic clouds

- The most common Arctic clouds low stratus and stratocumulus. Total cloud cover is least extensive in December and January. Starting in May, cloudiness increases. Warm air over the water adjacent to ice, frequent temperature inversions, and fog, cause low level stratus clouds to form and persist through the entire warm period. From about mid-June to mid-September, the ocean area covered by sea ice is 80 to 90% covered with stratus.
- Clouds observed in the Arctic may be broadly divided into three categories : 1) mid- and upper-level or vertically-extensive clouds associated with synoptic disturbances, 2) persistent low-level clouds occurring under weak synoptic forcing (including surface-induced clouds due to open water), and 3) summertime convective clouds over continental interior regions. In regions with significant topographic features, orographic lifting is presumably also an important cloud formation mechanism. Although the precipitation associated with weakly-forced clouds is generally light compared to the synoptically-driven and convective cloud systems, it can contribute significantly to the annual accumulated precipitation due to the long duration and frequent occurrence of these clouds. Aerosols are expected to play a role in all arctic cloud types. However, aerosols may have a particularly strong impact on weakly-forced clouds, since these clouds represent a delicate balance between the cloud microphysics, turbulence, surface fluxes, and/or radiative. Weakly forced low-level arctic clouds are typically mixed-phase (even at cloud temperatures <-25° C) with continuous light snow or snow showers falling to the surface. During the brief summer season, liquid-phase stratus (often multi-layer) with frequent drizzle dominate the cloud fraction. The number concentration of CCN (and hence aerosols) may play an important role in initiating precipitation in both warm and cold arctic.
- The availability of IN may be a critical factor in the persistence of weakly-forced arctic mixed-phase clouds and their precipitation efficiency.

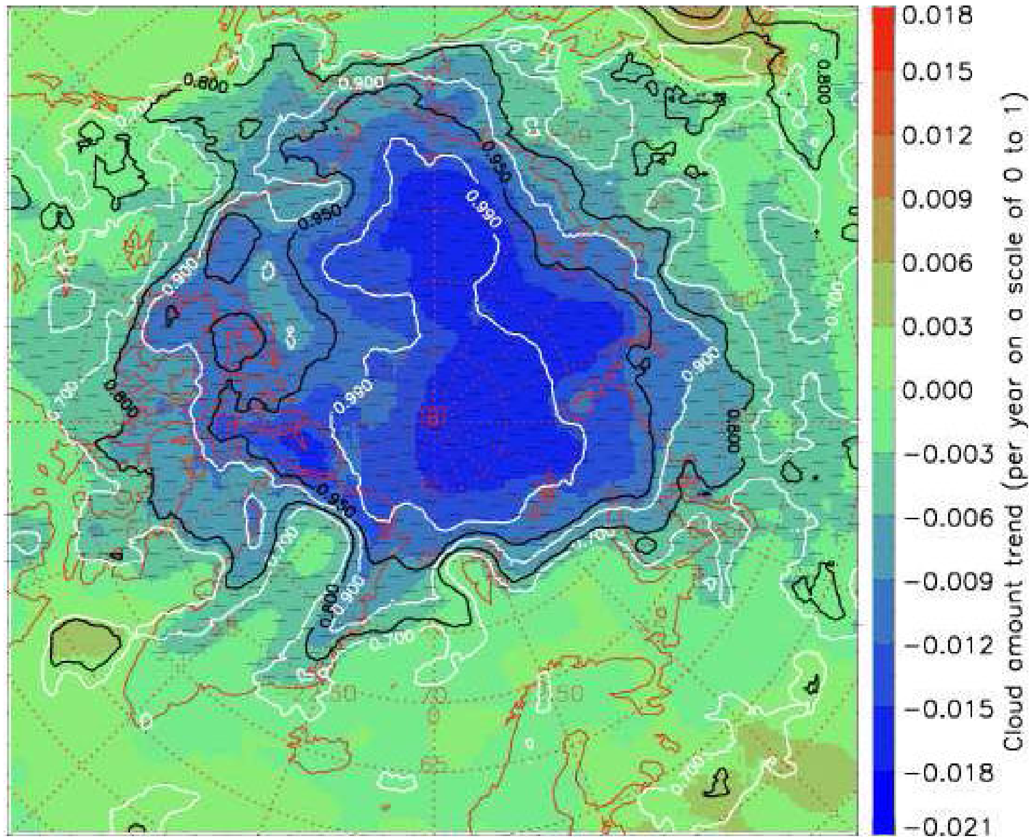


Figure shows the spatial distribution of the trend in cloud fraction over the period of 1982 – 1999 in winter. The contours are the confidence levels; colors denote the trend magnitude, and areas with dash marks indicate decreasing (From *Key et al.*)

Basics of cold clouds:

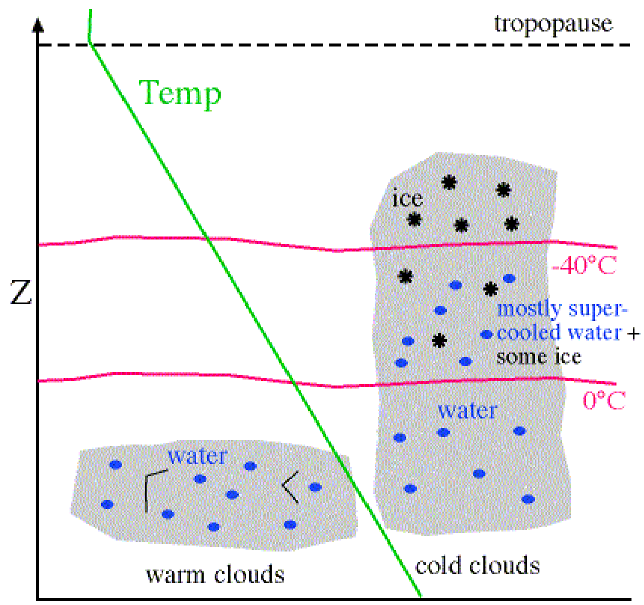
Cold clouds are defined as those clouds with tops colder than 0°C.

Can be comprised of:

- water
- super-cooled water - liquid droplets observed at temps less than 0°C
- ice

NOTE: Super cooled water is found at altitudes where: -40°C < Temp < 0°C

only ice is found at altitudes above -40°C

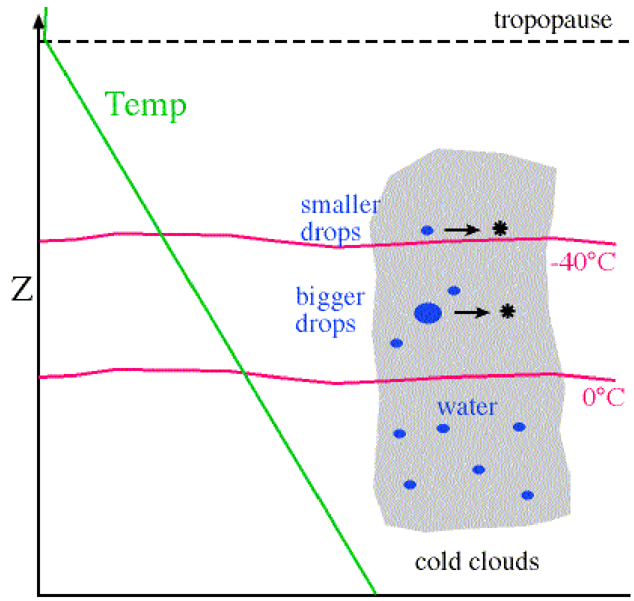


<u>Processes are occurring in a cold cloud to form ice particles:</u>

- homogeneous freezing
- deposition
- contact freezing
- accretion
- aggregation

Ice crystal formation by homogeneous freezing:

- Pure water drops do NOT freeze at 0°C
    - it needs to be colder
- bigger water drops will freeze at warmer temperatures than smaller drops
- smaller water drops require colder temperatures to freeze
- hence, there are more smaller drops than larger drops higher in the cloud



Ice crystal growth through deposition:

- Vapor can deposit onto ice nuclei (IN) in a cloud
- There tends to be more cloud condensation nuclei (CCN) than ice nuclei (IN):
    - therefore, there tends to be more super cooled water droplets formed by condensation than ice particles formed by deposition at altitudes where -40°C < Temp < 0°C

Ice crystal growth through contact freezing:

- Occurs when a supercooled drop comes in "contact" with an ice nuclei
- causes the supercooled drop to freeze

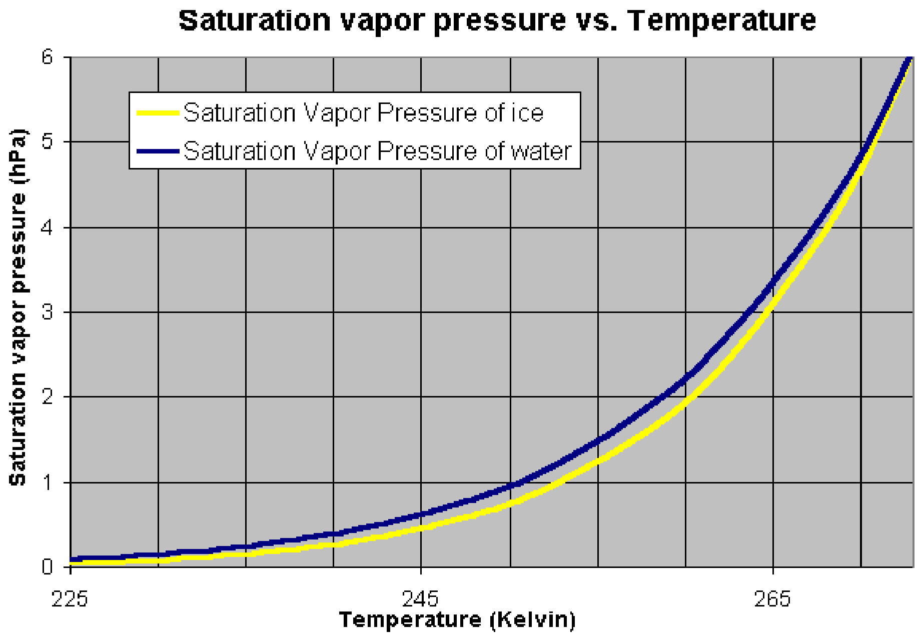
Accretion/Riming:

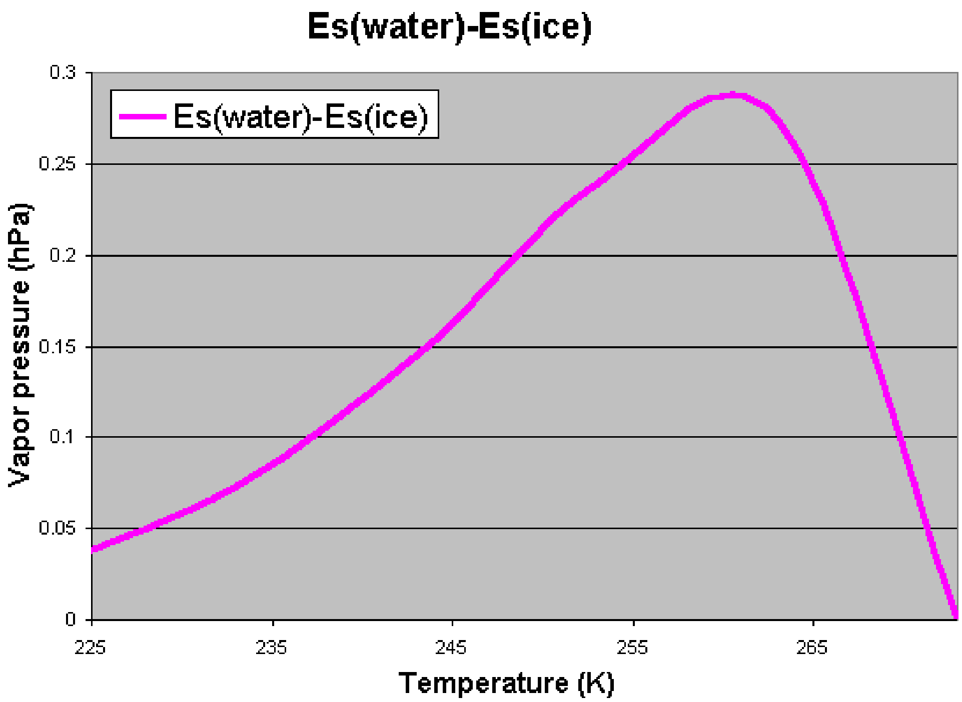
- Occurs when super cooled drops freeze onto ice particle
- the resultant particle is often referred to as graupel

Aggregation

- Occurs when two ice particles stick together, forming one larger particle

<u>Saturation water vapor e_s(water) > e_s (ice)</u>





- The largest differences e_s(water) - e_s (ice) is a maximum at -15°C
- Hence, it is near this temperature in a cold cloud that ice particles will grow more readily than water particles