

## **A discussion of cloud albedo and how it could be influenced by (anthropogenic) CCN concentrations**

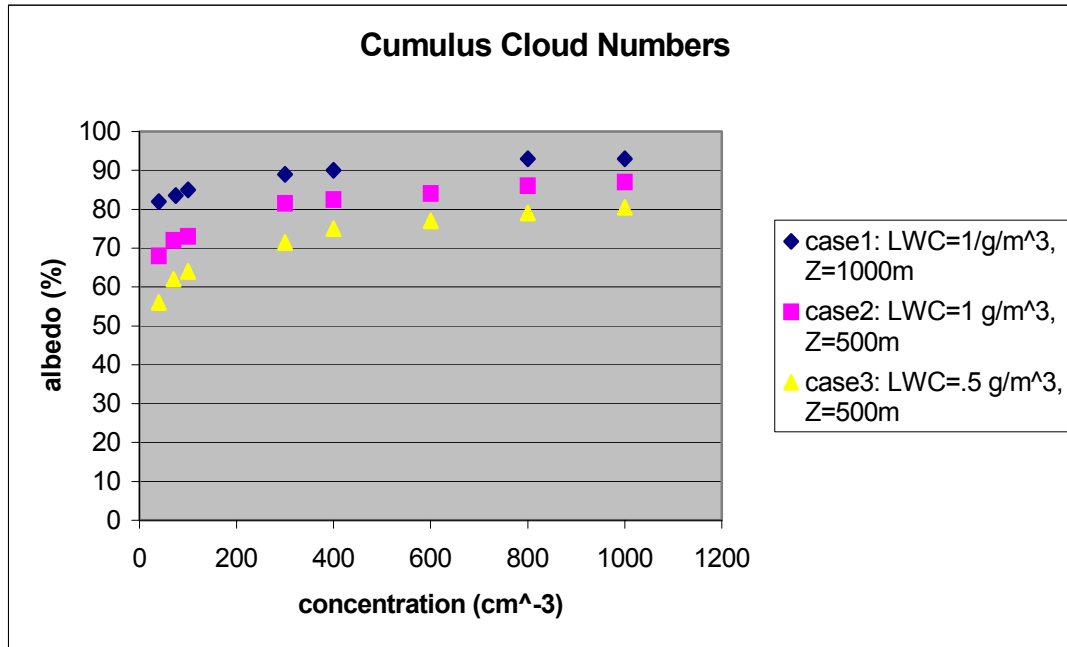
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In the growing concern about global climate change, computer models have become important tools in predicting future change. While the physics of greenhouse gasses are understood well, clouds are more difficult to account for and more variable. One large factor that is not included in climate models is possible increased cloud albedo (reflectivity) due to higher concentrations of cloud condensation nuclei (CCN) from human sources. The direct effects of aerosols have been included in models, but not this indirect effect of aerosols on clouds as an influence on radiative forcing. What follows is a discussion of the microphysics of clouds affecting albedo and the evidence for human pollution changing the albedo of clouds.

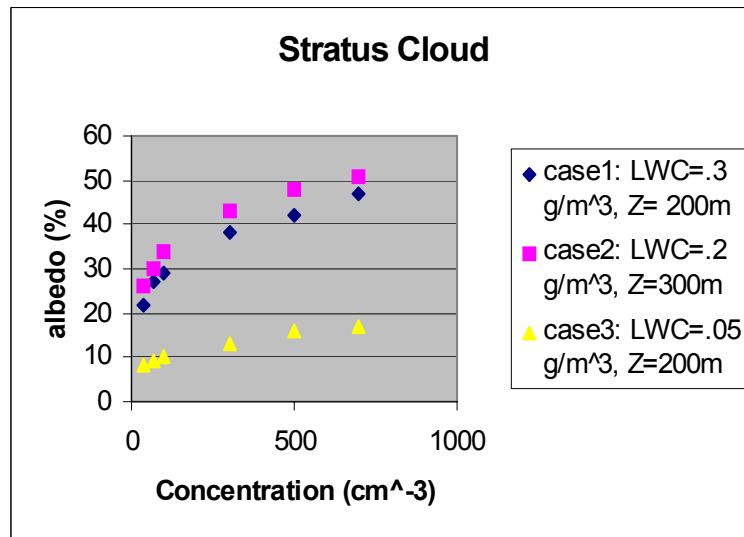
Clouds have a fair degree of color variation, ranging from bright white to the very dark grays of thunderclouds. They even differ in shading in the same cloud. The colors are a function of the microstructure of clouds—the water droplets that scatter light. The angle of sunlight can determine what color you see a cloud to be. For example, if you look at a very reflective cloud with sunlight directly behind you it will look bright white, but it can be shadowed by other clouds or by having it in between you and the sun. The theory behind cloud color is related to how many droplets are contained in the cloud and how big they are. Sunlight scatters by reflection, refraction, and diffraction among the droplets. Thus, in addition to the angle and strength of the sunlight, the variations in cloud shading relate to the concentration and size of the droplets and the size of the cloud. If there are more droplets, the clouds will be brighter white. Bigger drops have a larger surface area and thus reflect more light. A thicker cloud will reflect more sunlight (making it look dark if it is between you and the sun).

To examine how sensitive these factors are in cloud albedo, I ran a computer simulation called cloud. This program took the input parameters of liquid water content (LWC), cloud thickness ( $Z$ ), and droplet concentration and then applied a ray-tracing algorithm to find angles of scattering. It took a given number of rays and followed the path of each one, then giving a summed account of the emerging scattering direction of all the rays. The number I took as the albedo was the percentage of rays that scattered at angles greater than 90 degrees. The program works by calculating a droplet radius from the inputted values of LWC and concentration. It then follows a ray of light as it encounters randomly placed water droplets based on a probability related to the concentration. It further determines the path of the ray by calculating whether it reflects or refracts based on a probability determined by Fresnel's Laws. When the ray leaves the cloud, the program records its exit angle. With a large number of rays, the program can give an accurate statistical picture of albedo. I looked at a histogram of the cosine of the emerging ray angles to find albedo (the sum of the number of negative values being the percentage of light rays reflecting from the cloud rather than going through it).

I was primarily concerned with how sensitive the albedo was to concentration of water droplets. I saw trends in the data that I got from the simulation. If you look at the albedo differences between the smallest and largest concentrations of water droplets in



the three cases shown in the cumulus cloud simulation you see the spread is smaller in the cases with higher LWC, and Z (cloud thickness). For case1, the greatest albedo difference is 11%, but for case3 the greatest difference is 24.5%. Most cumulus clouds have high droplet concentrations—in the hundreds and not as low as 40. This is what gives them their brilliant white color in formation (when the droplets are most numerous). Cumulus clouds also tend to be very thick and have high liquid water contents, so the concentration is not as significant a factor in cumulus clouds as stratus clouds when considering cloud albedo. Hudson (1993) describes the shift in interest from cumulous clouds to stratus clouds when thinking about the impact of clouds on climate (for many reasons, but among them the thickness of stratus clouds making them "optically thinner").



You can see from the stratus cloud simulation that a change in concentration can have an even greater effect on albedo in this case than in the case of cumulus clouds. Case1 and case2 in the stratus cloud numbers both have an albedo difference of 25% over a smaller concentration difference than in the cumulus cloud numbers. In addition, if you are looking at an overall change in albedo of total cloud cover, stratus clouds cover a much greater area and so can have a bigger effect.

Since droplet concentration can have a significant effect on the optical properties of clouds, it is important to understand what influences droplet concentration. To investigate the theory behind cloud droplet concentrations and sizes, I looked at data collected by experiments run by the Research Aviation Facility, a branch of the National Center for Atmospheric Research. The three experiments that I examined data from were SCMS, FASTEX, and WISP94. SCMS collected data during summer in flights above Florida. FASTEX took data in flights over the Atlantic Ocean off the west coast of Ireland in the winter. WISP94 was an experiment taking data from flights over Colorado and Wyoming in the winter.

Droplet concentration is related to several factors. Liquid water content, or how much water there is to form droplets, is obviously a very important factor. Relative humidity has a small impact, but more importantly LWC (liquid water content) is a factor of the updraft velocity of a cloud and the altitude of a cloud. As a parcel of air rises the temperature drops and the saturation level is lower. (The saturation level is a measure equivalent to the dew point—the temperature and pressure when water ought to condense from vapor into liquid.) This allows more water to condense into water droplets. The LWC count goes up and the droplets grow in size. This is exemplified well in the cumulus cloud measurements at different altitudes in the SCMS project data. The altitudes are 610 m, 1520 m, and 2440 m. Corresponding to these changes in altitude the temperature drops from about 22 degrees C, to 17 degrees C, to 12 degrees C. The increase in altitude also corresponds to an increase in liquid water content. Additionally, the average size of the droplets increases through the three cases. Note that even though the LWC is practically an order of magnitude higher at the higher altitude than the lower altitude the concentration of drops is actually smaller.

But drop size and concentration is not purely a function of altitude. The complexities of the mixing of surrounding air with the humid air of clouds aside, the type of cloud is also very important. Cumulus clouds tend to have much greater droplet concentrations than stratus clouds, this is in large part due to a higher updraft velocity. It has also been observed that maritime clouds have much lower droplet concentrations than continental clouds. You can see this illustrated with the difference between the droplet spectra from the SCMS flight and the FASTEX flight data. Droplet spectra are a graphical way of looking at the concentrations of droplets of different sizes. The SCMS flight was through continental clouds, while the FASTEX data was taken from flights over the ocean. The continental graph has a sharp peak and a smaller average drop diameter. If you compare the data from the SCMS example from a low altitude to the FASTEX data at a similar altitude you see that even though it has a larger liquid water content, the maritime cloud has a smaller droplet concentration. These are typical variations between maritime and continental clouds. Maritime clouds have lower concentrations and bigger droplets.

In clean air, water vapor can be supercooled to supersaturations of even up to 300% relative humidity. The water molecules have a high surface tension and by collisions alone they do not form droplets stable enough to withstand the evaporative force. That is, two forces are going on at the same time for these water molecules. There is an attractive force which causes them to stick together when they collide, but there is also a tendency to evaporate when the partial pressure of the water vapor is low. In order for droplets to coalesce, the attractive force must be stronger than the evaporative force.

So in order to form drops at low supersaturations (just above the saturation equilibrium pt at levels like 101% relative humidity) there must be something to help the water droplets: nucleation. Small hygroscopic (water soluble) aerosols attract the water molecules allowing stable droplets to form. When a particle, or condensation nucleus, collects water and forms a droplet, it is said to be activated. The saturation ratio where a particular condensation nucleus is activated depends on the size and type of the nucleus. Those nuclei that are activated at low supersaturation levels, and thus the primary condensation nuclei of importance in clouds are cloud condensation nuclei.

Squires and Twomey did a lot of early work in the field of cloud microphysics understanding the differences between maritime and continental clouds. He summarizes some of the early research done on maritime and continental clouds in his article detailing research on the first concurrent measurements of condensation nuclei and cloud droplet spectra (Twomey & Squires, 1959). In it he concludes that condensation nuclei concentrations are the primary cause of differences in droplet concentration in maritime and continental clouds. That is, the concentration of particles in the air is causally connected to the concentration of water droplets in clouds. Squires was the one to discover that droplet spectra are related to a small subset of all condensation nuclei, called cloud condensation nuclei (CCN).

The data from the WISP94 flight is another example of how important aerosols are in the formation of water droplets. The example shown is at a high altitude in very clean air—the particle concentration is  $300 \text{ cm}^{-3}$  while polluted air particle concentrations are around  $10^5 \text{ cm}^{-3}$ . The very low concentration of water droplets is related to this low particle concentration. If there are only a few particles to help nucleate droplets, then only a few bigger droplets will form instead of lots of smaller droplets. The droplet concentrations formed in the clean air of the WISP94 flight is similar to the droplet formations of concentrations and sizes in maritime clouds. In fact, this air is even cleaner than some maritime air.

Aerosols in the atmosphere come from natural and human sources. Volcanoes and forest fires are two important natural sources of condensation nuclei. Particles that come from human sources are called anthropogenic. Anthropogenic condensation nuclei are an important consideration in global climate change because, as we have seen, CCN concentrations have an important effect on droplet concentrations and droplet concentrations have an important effect on cloud albedo. An early study by Warner and Twomey (1967) illustrates human impact on cloud droplet concentration well. Observations of cane fires on the east coast of Australia and the higher measured aerosol concentrations led them to conclude that “it seems clear that there is no real difficulty in accounting for the high concentration of nuclei observed over the land.” They measured higher droplet concentrations in continental clouds above the region, and not only that but they observed higher droplet concentrations in maritime clouds near the cane fires than other measurements in that same location from other seasons. This is due to the aerosols carried by the wind from the burning. Another study examined the CCN produced by coal power plants and their effect on cloud droplet concentrations (Hobbs, et al. 1979). They found that the CCN count in plumes from the coal power plants were 2 to 5 times higher than in the ambient air, and up to 80 times higher if the air was very clean. While the higher CCN concentrations did not have a dramatic effect on cumulus clouds, they increased the droplet concentrations of stratus clouds by an order of magnitude! One of

the most dramatic examples of anthropogenic CCN emissions affecting clouds is in ship trails. Conover first suggested that “anomalous cloud lines” found in satellite photos were formed from small bright clouds forming from the exhaust of ships as they traveled through clean maritime air (1966). Later studies and calculations have confirmed his theory.

Anthropogenic CCN can clearly have an important effect locally on cloud albedo, but does this translate into a large-scale anthropogenic effect on cloud albedo? Hudson investigated how much of CCN concentrations were anthropogenic (1991). From many observations at places all along the west coast of the United States in different situations he concludes, “The most important result of these measurements is that the production of CCN by anthropogenic processes is quite apparent but the natural continental source of CCN is not apparent. CCN of all critical supersaturations (sizes) are produced immediately by anthropogenic processes.” This does not conclusively say that the majority of continental CCN come from anthropogenic sources, but it does point in that direction. It has been argued that the impact on global cloud albedo is, or could be in the future, as great an impact as global warming from increased concentration of greenhouse gasses (Twomey, et al., 1984). Greenhouse gasses warm the atmosphere, but the increased albedo of the clouds reflects sunlight back into the atmosphere having a cooling effect on the earth.

This argument leads us to several important questions. First of all, if two different sources of global air pollution are having opposite effects on the way the atmosphere regulates global average temperature, will they continue to be balanced in the future? It has been suggested that the cooling effect of increased anthropogenic CCN emissions has masked the expected warming from greenhouse gasses in these last decades (Hudson, 1991). If this is the case, it may be that at some point in the future the increased warming effect of greenhouse gasses will become much more important than the cooling effect of CCN concentrations, or vice versa. This may have a dramatic effect on global average temperature much more than we have yet seen. We ought to be even more cautious about global climate change in the light of this uncertainty we have in this question of the ultimate effect of our pollution on the climate.

But our caution should be aroused for another reason. To see that we have a significant impact on the atmosphere, must lead us to question what right we have to determine the condition of the atmosphere, that is, what ownership we have of the sky. This has started to become an international topic of discussion already with the issue of acid rain, but change in temperature from CCN and greenhouse gas emissions is a less regional issue than acid rain. I suggest that we have an ethical responsibility to other nations and even to the state of nature itself in our human impact on the atmosphere.



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