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Sampling the composition of cirrus ice residuals

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ABSTRACT

Cirrus are high altitude clouds composed of ice crystals. They are the first tropospheric clouds that can scatter incoming solar radiation and the last which can trap outgoing terrestrial heat. Considering their extensive global coverage, estimated at between 25 and 33% of the Earth's surface, cirrus exert a measurable climate forcing. The global radiative influence depends on a number of properties including their altitude, ice crystal size and number density, and vertical extent. These properties in turn depend on the ability of upper tropospheric aerosol particles to initiate ice formation. Because aerosol populations, and therefore cirrus formation mechanisms, may change due to human activities, the sign of cirrus forcing (a net warming or cooling) due to anthropogenic effects is not universally agreed upon although most modeling studies suggest a positive effect. Cirrus also play a major role in the water cycle in the tropopause region, affecting not only redistribution in the troposphere but also the abundance of vapor entering the stratosphere. Both the current lack of understanding of cirrus properties and the need to improve our ability to project changes due to human activities in the future highlight the critical need to determine the aerosol particles on which cirrus form.

This review addresses what is currently known about the abundance, size and composition of cirrus-forming particles. We review aircraft-based field studies which have either collected cirrus ice residuals for off-line analysis or determined their size, composition and other properties in situ by capturing ice crystals and sublimating/removing the condensed phase water. This review is predominantly restricted to cirrus clouds. Limited comparisons are made to other ice-containing (e.g., mixed-phase) cloud types. The findings of recent reviews on laboratory measurements that mimic upper tropospheric cirrus formation are briefly summarized. The limitations of the current state of the art in cirrus ice residual studies are outlined. Important ancillary measurements and how they are integrated with ice residual data are also presented. Concluding statements focus on the need for specific instrumentation and future studies.

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1. Introduction

The definition of what is a cirrus cloud, and what is not, is complex. The classical definition of cloud type is based on morphology. According to the World Meteorological Organization (1975) there are three morphologically different sub-types (genera) of high altitude clouds: 'cirrus' (detached clouds composed of filaments with a fibrous appearance), 'cirrocumulus' (thin sheets or layers) and 'cirrostratus' (semi-transparent fibrous with large sky coverage). The textbook by Lynch et al. (2002), the most comprehensive recent review of this cloud type, expands on the morphological description and adds 'subvisible' or 'subvisual' cirrus (optical depth, normally considered at 0.694 micrometer wavelength, of <0.03) and 'contrail cirrus' (due to input of water vapor from an aircraft). The properties of these clouds are summarized in Table 1. For the purpose of this review, cirrus are considered to be high altitude clouds of thin vertical extent composed predominately of ice crystals.

Regarding ice, Lynch et al. (2002) notes that "all cirrus clouds are composed of ice, but not all ice clouds are cirrus". Ice fogs and other glaciated near-surface clouds are not considered to be cirrus. Terrain induced ice clouds such as orographic or mountain wave clouds are often differentiated from cirrus because their formation mechanism couples them to the Earth's surface. Since they are occasionally grouped with the other cirrus types, they are briefly considered in this review. Of the cirrus types, only cirrocumulus and orographic can be mixed phase (containing ice and water droplets) whereas the remainder, apart from transient droplets or deliquesced aerosol particles during formation, are exclusively ice.

Cirrus are generally delineated by five different formation mechanisms (Fig. 1). 'Synoptic cirrus' are formed by motion in the mid to upper troposphere, for example due to the jet stream or frontal passage. These clouds are induced by the cooling of rising air, normally in the range of few centimeters to a meter per second. Synoptic cirrus are believed to form on in situ aerosol particles and are observed to form from the top (i.e., the coldest point) and proceed downward as ice sediments (Starr and Cox, 1985). 'Anvil' or 'injection cirrus' is formed by the high-altitude detrainment of ice from a cumulonimbus cloud. The formation of anvil cirrus is complex due to the uplift of aerosol particles, droplets and ice from the lower to upper troposphere, often at several meters per second. Ice formation competes with removal by sedimentation of the largest cloud elements — water droplets or ice crystals. Ice formation in anvil cirrus can take place on aerosol particles redistributed from the boundary layer or free tropospheric particles entrained within the convective system. 'Tropopause cirrus' are normally considered synonymous with the 'subvisible' type defined above. These clouds are restricted to the low temperatures observed at the high tropical tropopause (−70 to −90 °C). Tropopause cirrus may be coupled to large scale vertical motions, for example from deep convection (Heymsfield, 1986) or gravity waves (Randel and Jensen, 2013). 'Orographic' or 'wave clouds' are distinctly different from the remainder in that they are formed by meter per second or greater vertical motion imparted by terrain. These clouds are often mixed in phase and can form on aerosol particles from the boundary layer. 'Contrail cirrus' are the only purely anthropogenically formed cirrus, due to the input of water vapor in the mid to upper troposphere. Particles on which contrails form may be from the background free troposphere or due to the aircraft emissions. Contrails are composed of the highest number and smallest size ice crystals of the cirrus types (Sassen, 1997). The formation mechanisms are shown schematically in Fig. 1 and these naming conventions are used throughout this review. A more comprehensive description of various cirrus formation mechanisms is given in Lynch et al. (2002).

Cloud elements are understood to initially form on pre-existing aerosol particles. These processes are shown schematically in Fig. 2. For conditions above 0 °C only liquid droplets can form. Considering the case of an uplifted and cooled air parcel, the water vapor in that parcel is expected to remain constant, but as it is cooled the relative humidity (RH) rises. If soluble aerosol particles are present those particles will rapidly take up water and grow significantly at their deliquescence point (e.g., ~80% in the case of sodium chloride or ammonium sulfate) (Seinfeld and Pandis, 2006). These aqueous solution particles are often termed 'haze droplets' and may reach several micrometers in diameter. At a point slightly above 100% RH (i.e., slightly supersaturated with respect to liquid water), Koehler theory predicts that both haze droplets, insoluble aerosol particles, and internal mixtures will nucleate liquid water and grow, or 'activate', to super-micrometer cloud droplets (Seinfeld and Pandis, 2006). Note that the initial aerosol particles can be soluble or insoluble or a combination of the two and either dissolve or remain immersed.

At temperatures below 0 °C ice nucleation can occur once water vapor reaches saturation with respect to ice. Below this temperature liquid water has a higher vapor pressure than ice,

Table 1
Mean and the range of cirrus cloud properties.

Property	Mean	Range
Altitude (km)	9.0	4.0 to 20.0
Thickness (km)	1.5	0.1 to 8.0
Concentration (L^{-1})	30.0	10^{-4} to 104
Ice content ($g\ m^{-3}$)	0.025	10^{-4} to 1.2
Crystal size (mm)	250	1 to 8000

Adapted from Lynch et al. (2002).

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