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Micro-Physique et Givrage Cloud Microphysics and Aircraft Icing

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MICRO-PHYSIQUE ET GIVRAGE

CLOUD MICROPHYSICS AND AIRCRAFT ICING

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Résumé

Nous décrivons dans ce papier les conditions dans laquelles des phénomènes de givrage peuvent êtres générés, puis considérons les valeurs typiques du contenu en eau pour les divers types de nuages d'eau surfondue. Ce contenu en eau peut être mesuré par des instruments aèroportés utilisant soit les fils chauds, soir une technique d'évaporation/Lyman alpha hygrométrie. Des méthodes de télédétection des zones givrantes au sein des nuages sont en cours de développement mais non encore opérationnelles: les techniques les plus prometteuses sont la radiométrie ainsi qu'une méthode radar basée sur la mesure de l'atténuation différentielle à deux longueurs d'onde.

Abstract

We review the conditions which lead to icing within clouds and then consider the typical values of liquid water content to be found in supercooled clouds. In-situ measurements of the liquid water content within clouds can be measured by aircraft instruments using either hot wires or an evaporation/Lyman alpha hygrometry technique. Methods of remotely sensing icing regions within clouds are being developed but cannot yet be considered to be operational. Methods showing promise are the use of passive radiometry and also an active radar technique based on the differential attenuation measured at two wavelengths.

1. INTRODUCTION

Supercooled clouds of water droplets are a relatively common occurrence. When a parcel of air cools and becomes supersaturated with respect to liquid water, cloud droplets form on some of the many aerosol particles present in the air. The presence of the droplets then limits the supersaturation with respect to liquid water to less than 1%. The cloud droplets formed have diameters typically in the range 10 to 20 μm and are present in concentrations of 100 to 1000 per cm^3. The total mass of liquid water in these droplets is called the 'liquid water content' (LWC) and is usually measured in g m^{-3}. A typical value of LWC is 1g m^{-3}, if we consider the density of air at 2km altitude to be about 1kg m^{-3}, then this LWC occupies about one part in 10^6 of the total volume of the air.

When the temperature falls below O°C the cloud water drops do not freeze immediately. Although there is no shortage of cloud condensation nuclei, only a very few of these nuclei are able to act as 'ice nuclei' and transform a liquid droplet to ice. As the temperature falls, the efficiency of these cloud nuclei increases, so that at -20°C most clouds have an appreciable number of ice crystals present, and at -40°C liquid water is very uncommon. Once an ice crystal is formed in a supercooled cloud of liquid droplets, it finds itself in an environment which is saturated with respect to liquid water but supersaturated with respect to ice. For example, at temperatures of -10°C and -20°C the supersaturation with respect to ice is about 10 and 20% respectively. The ice particles grow rapidly in these high supersaturations and the cloud liquid water content falls.

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If the supercooled droplets impact upon solid objects they are nucleated and freeze rapidly giving rise to the phenomena of icing. At aircraft speeds if we assume that all the cloud droplets contained in the volume of air swept out by the aircraft will impact upon the aircraft surface (that is the collection efficiency 'E' is unity), then, for a 1km path through a supercooled cloud with a LWC of 1 g m^{-3}, this would result in a 1mm layer of ice on the aircraft. In practice the layer would not be uniform, the small droplets have a finite inertia and tend to follow the airflow, so that as a result, thicker layers of ice build up on projecting surfaces of the aircraft.

2. VALUES OF CLOUD LIQUID WATER CONTENT

The values of LWC content in clouds are quite variable. If we consider a tropical cloud with a base of 15°C at an altitude of 1km, then, if we assume assuming that the rising parcel of air is undiluted and no precipitation or ice forms, the 'adiabatic' LWC would be 6 g m^{-3} at 0°C, and at -20°C the LWC would be 10 g m^{-3}. In a real cloud some mixing of dryer air and the formation of rain and ice will lead to lower values, but in the rising currents within cumulonimbus clouds, values of LWC may reach 5 g m^{-3} over limited distances. Clouds with colder bases will have much lower values of LWC. For a cloud base of 0°C at an altitude of 1km, then the LWC at -10°C and -20°C would, with the adiabatic assumptions above, be 1.5 g m^{-3} and 2.5 g m^{-3}.

However, as pointed out above, as soon as a very limited number of ice particles are present, resulting either from the occasional ice nuclei or from ice particles falling from higher levels, then the ice particles find themselves in a high supersaturation and grow rapidly and deplete the liquid water content. The highest values are found locally in the updraughts of cumulonimbus clouds with warm cloud bases. More extensive regions of supercooled water are found in more stratiform conditions, but here, because ice is also present, the values of LWC are generally much lower than the adiabatic values theoretically calculated above. They are usually below 0.5 g m^{-3} and often close to 0.1 g m^{-3}.

It is difficult to quote 'average' values of LWC in different types of clouds. Feigelson (1978) presents some statistics of the average proportion of the total cloud water content which is in the form of ice, and these percentages range from about 40% at -10°C to 75% at -25°C, but of course individual clouds can vary markedly from these 'average' figures.

3. IN - SITU METHODS OF MEASURING LIQUID WATER CONTENT

Because liquid water content is such an important parameter many devices which been developed to measure it within cloud. There are a range of instruments which measure size and concentration of individual droplets, but the integrated liquid water contents derived from the spectra are liable to error. We will only consider instruments which sense the total liquid water. They may divided into two classes. Those which rely on the cooling of a hot wire exposed to the cloud and those which heat the air to evaporate the liquid and then measure the vapour content.

3.1 HOT WIRE INSTRUMENTS

The most common aircraft instrument for measuring the small droplet portion of cloud water is the Johnson-Williams (J-W) hot wire device which uses a hot nickel-iron wire with a known temperature coefficient of resistance. This wire is heated by a constant current and the resistance measured using a bridge circuit. In dry air the wire maintains a steady-state temperature, a result of the balance between the electrical heat supplied and the heat removed by the dry airflow. However, if droplets are present they collide with the wire and cause a degree of cooling directly related to the amount of liquid water in the airstream. To compensate for these two effects two wires are used, one exposed to the cloud droplets, and one parallel to the airstream. An analysis of the response of the J-W is provided by Strapp and Schemenauer (1982). King et al (1978) describe an improved version of the hot wire device, using a coiled coil of wire which has a more predictable collision cross section for the cloud droplets; this device can therefore be calibrated absolutely and there are suggestions that this can provide more accurate values of LWC.

3.2 EVAPORATION LYMAN-ALPHA INSTRUMENTS

Many versions of this instrument have been designed but the most successful would appear to be that described by Nichols et al (1990) which is currently operational on the Meteorological Office C-130 aircraft. The incoming air is heated up with a power of up to a kW so that all the cloud water and ice is evaporated. The total vapour density present in the air is then measured remotely using a Lyman alpha hygrometer. The device does not rely on capturing the droplets and has the advantage of rapid response. It does not however distinguish between water and ice cloud particles but measures the total water content.

4. REMOTE SENSING

Remote sensing techniques have the advantage of locating regions where there is a danger of icing so that the aircraft can avoid them. However, in contrast with the in-situ cloud sampling methods described above, the methods described below are only at the experimental stage and, although they show promise, they cannot be regarded in any sense as operational.

4.1 PASSIVE RADIOMETRY

Warner et al (1984 and 1985) describe a technique in which a complete vertical cross-section of the liquid water in a cloud could be obtained in two or three minutes. This is much more rapid than methods involving instrumented aircraft. The method involves measurement of microwave emissions from the cloud in many different directions and a mathematical inversion to obtain the liquid water content. Simulation studies show that if radiometers with a noise level of 0.2K were used then it should be possible to recover liquid water content to within 0.1 g m^{-3} with a resolution of a few hundred meters, but of course the existence of such regions would only be evident when the aircraft carrying the radiometer had flown past the region. In addition, because the microwave emission from the cloud water varies with temperature, a rather accurate knowledge of the vertical temperature profile is needed.

4.2 ACTIVE RADARS

Active radars seem initially attractive, but the backscattered power (or 'reflectivity') is proportional to the sixth power of the diameter of the particles (D^6). Accordingly the reflectivity of clouds is not related to their liquid water content. In addition, if larger precipitation particles are present they will dominate the return because of the D^6 relationship. However, the attenuation of the radar beam as it propagates through the clouds is proportional to the volume of the liquid, that is to the liquid water content for clouds. Gosset and Sauvageot (1992) propose a dual wavelength method for measuring this attenuation. The technique involves measuring the ratio of the radar reflectivities measured at the non-attenuating wavelength of 3cm (10GHz) and that measured at the attenuating wavelength of 8mm (35GHz). Theoretical predictions are encouraging and observations to verify the technique are now being carried out. If this method is successful it would appear to have advantages over the other ones described in this paper. It should be possible to detect icing regions ahead of an aircraft by using a self-contained dual wavelength radar mounted on the same aircraft.

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