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A method to determine true air temperature fluctuations in clouds with liquid water fraction and estimate water droplet effect on the calculations of the spectral structure of turbulent heat fluxes in cumulus clouds based on aircraft data

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ABSTRACT

Liquid water droplets could distort aircraft temperature measurements in clouds, leading to errors in calculated heat fluxes and incorrect flux distribution pattern. The estimation of cloud droplet effect on the readings of the high-frequency aircraft thermometer employed at the Central Aerological Observatory (CAO) was based on an experimental study of the sensor in a wind tunnel, using an air flow containing liquid water droplets. Simultaneously, calculations of the distribution of speed and temperature in a flow through the sensitive element of the sensor were fulfilled. This permitted estimating the coefficient of water content effect on temperature readings. Another way of estimating cloud droplet effect was based on the analysis of data obtained during aircraft observations of cumulus clouds in a tropical zone (Cuba Island). As a result, a method of correcting air temperature and recovering true air temperature fluctuations inside clouds was developed. This method has provided consistent patterns of heat flux distribution in a cumulus area. Analysis of the results of aircraft observations of cumulus clouds with temperature correction fulfilled has permitted investigation of the spectral structure of the fields of air temperature and heat fluxes to be performed in cumulus zones based on wavelet transformation. It is shown that mesoscale eddies (over 500 m in length) were the main factor of heat exchange between a cloud and the ambient space. The role of turbulence only consisted in mixing inside the cloud.

1. Introduction

One of the main mechanisms of cumulus cloud development is turbulent energy exchange inside the cloud and across the cloud boundaries, and an aircraft laboratory equipped with special gages is the most suitable platform for cloud observations. Modern aircraft instruments to measure high-frequency wind speed and temperature fluctuations make it possible to investigate the fine structure of temperature and turbulent heat flux fields in a cumulus zone, i.e., inside the cloud and the ambient area influenced by it. As temperature in clouds and the ambient area are also of importance in studying cloud development, temperature measurements must be accurate enough, since temperature differences of 0.3–0.5 °C within a cloud zone are essential for cloud formation processes. On the other hand, to estimate turbulent heat fluxes in cloud zones, an aircraft thermometer must be a quick-response instrument.

The principle of aircraft air temperature measurement builds upon a well-known gas-dynamic equation (Lenschow, 1972):

$$T = \frac{T_i}{1 + \frac{\kappa - 1}{2} r M^2} \tag{1}$$

where **T** is the true air temperature, **M** is the Mach number of the flow, $\mathbf{T_i}$ is the measured air temperature, **r** is the recovery

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thermometer factor, and κ is the ratio of specific heats. Factor **r** characterizes the rate of flow heating in a thermometer, and in the case of flow stagnation $\mathbf{r} = 1$. In the common case, factor **r** depends on the Mach number **M**, Reynolds number **Re**, Prandtl number **Pr**, and κ value, i.e., $r = f(M,\mathrm{Re},\mathrm{Pr},\kappa)$ (Benedict, 1984). Prandtl number and the ratio of specific heats for air under normal atmospheric conditions are constants ($\mathbf{Pr} = 0.72$ and $\kappa = 1.41$). Typical air speed, height of flight, and Mach numbers for an aircraft laboratory are 100–150 ms^{-1}, 0.1–10 km, and 0.2–0.5, respectively. The dependence of **r** on **Re** and **M** for these values is insignificant (Benedict, 1984).

Presently, airborne laboratories use temperature sensors Rosemount Model 102, produced by GoodRich Corp. (Rosemount, 1981). These sensors allow true air temperature measurements with ~0.3–0.4 °C accuracy (Rosemount, 1981), and have a de-icing element and a special shield protecting their sensitive elements from cloud droplets. This shield, however, retards the thermometer response, resulting in over 1 s time constant in Rosemount Model 102 sensors, which makes measurements of turbulent temperature fluctuations and calculation of turbulent heat fluxes impossible.

Fast-response aircraft thermometers often use resistive sensors. In this case, the sensitive element of such a thermometer is a thin metallic wire (platinum, tungsten, or nickel one ~0.25 μm in diameter), which can make the thermometer time constant as small as ~0.001 s (Friehe and Khelif, 1993). For special high-frequency atmospheric studies (e.g. in a planetary boundary layer), thermometers with open wire elements were devised (Wolff and Bange, 2000). If a thermometer had a cloud particle shield, it enabled measurements not only in a clear atmosphere, but in clouds, too. (Lawson and Rodi, 1992). Another aircraft thermometer type is a so-called ultrasonic thermometer–anemometer whose operation principle based on measuring sound speed in air (Cruette et al., 2000). Apart from the measurements of temperature fluctuations, this instrument allows measuring airspeed. A disadvantage of the ultrasonic thermometer is its sensitivity to aerodynamic noise, especially aboard high-speed aircraft.

A family of ultrafast thermometers was developed to study small-scale cloud temperature inhomogeneities (Haman et al., 2001). The thermometers had a spatial resolution of about a few centimeters, and were equipped with a special vane shield preventing impacting of cloud droplets on the sensitive element.

However, in any case, air temperature readings taken inside a cloud with liquid water fraction are disturbed by droplet effect. Air flow stagnation in the temperature sensor leads to flow heating and evaporation of cloud droplets. Even if droplets do not impact on the sensitive element directly, evaporation of droplets due to flow heating at the sensor shield causes temperature decrease in a flow passing through the sensitive element. This results in the appearance of false temperature fluctuations — the phenomenon referred to as the thermometer wetting effect. According to some previous estimations (Sinkevich and Lawson, 2005), cloud droplets can affect aircraft thermometer readings, leading to errors of about 1 °C or even more.

There are a few methods to take into account the effect of droplets on aircraft temperature measurements. Supposing a thermometer sensitive element were always completely wetted, it is possible to evaluate a psychometric effect, i.e., the influence of water evaporation from the sensor surface on its temperature. One way is to use a special thermometer type (thermometer–psychrometer), which is always fully wetted (Telford and Warner, 1962). In this case, a correction for thermometer wetting, $\boldsymbol{\Delta T}$, is defined as (Mazin and Shmeter, 1977):

$$\Delta T = \Delta T^{*}(1-\beta_0) \tag{2}$$

where $\Delta T^{*} = 0.2rM^2T$ is the dynamic thermometer heating (see formula (1)), and $\beta_0 = \frac{1}{1+\frac{1550}{p}\frac{dE}{dT}}$ is the factor for a completely wetted thermometer (**p** is the pressure at the flight level; **E** is the pressure of saturated vapor).

If an aircraft thermometer is not fully wetted, the wetting coefficient β for this thermometer can be defined as (Mazin and Shmeter, 1977):

$$\Delta T = \Delta T^{*}(1-\beta). \tag{3}$$

Since the value of β is constant for each specific thermometer, the magnitude of wetting correction is also practically constant (changing of flight velocity affects the correction insignificantly). Thus, this method only allows correcting the average value of air temperature in a cloud, and is useless for retrieving true temperature fluctuations and calculating turbulent heat fluxes inside clouds.

CAO has collected vast experimental aircraft data on wind speed and turbulent air temperature fluctuations in cumulus clouds. Air temperature measurements were made using a high-frequency aircraft thermometer, HFAT, specially constructed at CAO to study clouds. In order to correct calculated turbulent heat fluxes and analyze the fields of temperature and fluxes in cumuli, it was necessary to have a method enabling the recovery of true air temperature fluctuations from HFAT readings, considering cloud water droplet effect.

The present study is basically devoted to developing a method that would make it possible to correct measured air temperature fluctuations in clouds containing water droplets and estimate the effect of liquid water on calculated turbulence characteristics (spectra, and turbulent fluxes) in cumulus area.

To determine the degree of water wetting effect on our aircraft thermometer, we used two independent approaches. The first one was realized through an experimental study of the characteristics of CAO's high-frequency aircraft thermometer and its behavior in a specialized wind tunnel when exposed to a specially produced air flow containing liquid water droplets. This study was supported by a numerical experiment to evaluate an air flow through thermometer channels. The other approach consisted in analyzing temperature fluctuation data with different wetting corrections introduced and calculation of turbulent heat fluxes, based on the data obtained during aircraft experiments in cumulus clouds.

2. Specialized wind tunnel

A specialized wind tunnel, SWT, with an air flow speed up to 80 ms^{-1} in the testing section, was constructed for testing aircraft temperature and liquid water sensors (Fig. 1). The SWT included a tractor electric fan, a diffuser, a testing section, an injection chamber, and an inlet confuser. In the testing section,