NOTES AND CORRESPONDENCE

A Calorimetric Jet Engine Technique for Estimating the Condensed Water Mixing Ratio in Cumulus Clouds for Cloud Physical and Weather Modification Research

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ABSTRACT

A technique has been developed for deriving estimates of condensed water mixing ratio in cumulus clouds from measurements of potential temperature in the air in the compressor of a jet engine. Condensate that enters the engine at low temperatures (near −10°C) is evaporated in the compressor, causing a cooling of the air that is proportional to the amount of condensate evaporated. An important element of the technique is a correction for the time response of the temperature measurement system mounted in the compressed air. This new technique is simpler and more robust than an earlier technique based on measurement of the vapor concentration in the compressed air by an optical extinction (at Lyman-alpha wavelength) method. The values of condensed water mixing ratio derived from the new system are shown to be similar to those from the optical extinction system, previously reported in the literature.

1. Introduction

The CloudQuest company of Nelspruit, South Africa, operated, until 1998 and on behalf of the Water Research Commission of Pretoria, South Africa, a high-performance jet aircraft (Learjet 24) instrumented for performing cloud physical measurements in cumulus clouds (cumulus congestus and cumulonimbus) in support of research into rain augmentation in South Africa. The same aircraft has been employed under contract to the Ente Regionale per la Promozione e lo Sviluppo dell'Agricoltura (the Regional Agency for the Promotion and Development of Agriculture), Friuli–Venezia Giulia, Italy, to perform microphysical measurements in cumulus clouds in support of a binational (Italo–Slovenian) hail suppression research program on the border between Italy and Slovenia.

The airborne measurement of important cumulus-cloud characteristics is a difficult problem for a number of reasons. The first of these reasons is the lack of accepted standards of comparison for all but a few of the instruments mounted on research aircraft, for which reason error evaluations are often not possible. Others derive from the hostile environment in the clouds, from the unplanned movements of the aircraft platform in response to strong drafts and turbulence, and from hail impacts, ice formation, and electrical phenomena.

The problem of measuring water quantities is particularly vexing. Previously available instrumentation (also present on the Learjet) consists of the following.

a) The Johnson–Williams hot wire (J–W) is one of the most studied of the airborne cloud physical instruments. It has a nominal size cutoff in the neighborhood of 30-μm droplet diameter and hence yields only the cloud liquid water content (LWC), amounting to a few grams per cubic meter. Our experience is that the measurements of the J–W instrument agree generally with LWC as estimated by integrating the droplet spectrum from the Forward-Scattering Spectrometer Probe manufactured by Particle Measurement Systems, Inc., of Boulder, Colorado (PMS–FSSP, described below); the degree of agreement depends on the shape of the cloud droplet spectrum itself (Morgan and Mather 1984).

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b) The CSIRO–King hot-wire probe (hereinafter referred to as the King) is another popular instrument. From the point of view of our experience in warm-based cumulus clouds, the King has the sole virtue of indicating higher LWCs than does the J–W hot wire. In many cases in which the 2D-C laser probe (described below) indicates an absence of larger particles, LWC measured by the King agrees with the condensed water content (CWC) measured by the engine compressor techniques described in this paper. Unfortunately, the King does not have a clear cutoff at some definite diameter (Biter et al. 1987), and, when large drops (say, greater than 75-μm diameter) are present, it is not possible to know just what is being measured. The King also exhibits a saturation effect that is a function of the true air speed of the aircraft, caused by the limited electrical power available for evaporating the water that impinges on the sensor (Morgan 1992). The King produces estimates of LWC that are never less than those of J–W or FSSP. Despite the above, once the King was mounted on the Learjet, the J–W instrument was removed. The King was calibrated for airspeed effects by making dry-air acceleration runs as recommended by the manufacturer.

c) The PMS–FSSP sensor measures the concentration and spectrum of cloud particles (diameter less than 47 μm) by a laser-based, forward-scatter method and, by integration of the volumes of the particles, gives an estimate of the cloud LWC. The FSSP instrument was used as recommended by the manufacturer, only in the airspeed range recommended, and employing all the recommendations of the National Center for Atmospheric Research Cloud Particle Measurement Symposium reported by Baumgardner and Dye (1982).

d) The PMS 2D-C laser probe uses a shadowgraph principle to give information (images) about the larger particles in the cloud. A linear array of diodes is illuminated by a laser, and droplets passing through the laser beam shade some of the diodes. For particles whose silhouettes do not overlap the edges of the diode array, the upper size limit is near 1100-μm diameter. With the aid of a ‘‘circle-fitting’’ technique, particles of diameter over 5 mm, which can overlap one or both end elements of the diode array, are measured and counted. Sampling volume is determined by direct linkage to the true airspeed measuring system, and all the manufacturer's recommendations have been applied.

The overall picture here is one in which fairly good estimates can be made of water contents up to near-adiabatic values in clouds, but capabilities in clouds of high to very high water contents are poor or nonexistent.

2. Background to the new technique

During a rain enhancement experiment in South Africa, a first technique was developed for measuring total water mixing ratio and condensed water mixing ratio, using the cloud physics aircraft's jet engines as evaporators and measuring the vapor content of the heated and compressed air emerging from the last stage of the engines' compressors (Morgan et al. 1989). The vapor density is measured by sensing the extinction of the Lyman-alpha line of hydrogen. The quantity most directly sensed by this technique is the total water (vapor plus condensate) mixing ratio; the condensed water mixing ratio is estimated by subtracting the water vapor mixing ratio, calculated based on the free-air temperature and pressure, with the assumption that the cloudy air is saturated.

The technical staff at General Electric, Inc., the manufacturers of the engines of the Learjet, has assured us that no ice or liquid water can survive passage through the compressor section of the engine. Entry of water or ice into the combustion section would interfere with the proper functioning of the engine. Apart from the compressional heating of the air, the condensate must pass through eight stages rotating at 12 000 rpm (at our cloud-penetration power setting of 88% rpm), alternated with static stages intended to counteract swirling of the air. Because of the resulting series of violent shocks, all solid or liquid particles, independent of their original size, are completely broken down to extremely small size by the end of the third or fourth stage, so that not even the largest drop or graupel particle that enters the engine fails to evaporate within the first few stages. The same rapid conversion to the vapor state negates the possibility of any significant centrifuging of the condensed water to the outer edges of the flow.

Evaporators have been employed in cloud investigations a number of times (Kyle 1975; Gayet et al. 1977; Coulman and Parker 1982; Ruskin and Scott 1974; Ackerman 1974; Ackerman and Wescott 1986). The instruments have all been limited by small inlet diameters (Smith 1976) and low volume flow rates. The inlets on the Learjet engines are large (0.14 m^2) and the air volume flow through one engine is about 15 $m^3\ s^{-1}$. In all the above, the basic sensing technique was water vapor absorption of a beam of radiation (infrared or ultraviolet).

An earlier application of an absorption measurement (using infrared absorption) of air compressed in the jet engine of an F-100 fighter aircraft was reported by Roys (1963) and Roys and Kessler (1966).

A problem with the Lyman-alpha technique is the extinction of the Lyman-alpha line by a contaminant, probably a hydrocarbon, that originates in the jet engine compressor. The effect of this contaminant is minimized by ‘‘baselining’’ the instrument during flight outside of cloud, just prior to cloud penetration, against a free-air measurement of dewpoint. The dewpoint instrument, the well-known EG&G Cambridge hygrometer, is very slow in responding at the air temperatures (near $-10°C$) at which our cloud studies are made (to complicate things further, the dewpoint probe becomes iced up during passage through the cloud, and several minutes are required for it to to return to equilibrium with the outside air), so there is an unknown uncertainty in the baseline measurement. Were it not for this humidity measurement problem (which could be obviated by installing a superior humidity-measuring instrument), the Lyman-alpha measurement would be easier to make and more accurate. In the early trials with the technique, the instrument was baselined by flooding the measurement cell with dry nitrogen, and it was this procedure that allowed us to see the effect of a contaminant. Subsequently, the nitrogen test was eliminated, and only the baseline against humidity was routinely performed.

Considerations concerning isokineticity of the flow into the engine are the same for the current technique as for the previously reported Lyman-alpha extinction measurement, as dealt with in Morgan et al. (1989). There, the airflow into the engine, relative to the geometrically intercepted airflow, was estimated based on true airspeed, outside air pressure, and static pressure in the nacelle (a static pressure sensor was temporarily mounted in place of an icing detector), and on application of the equation for frictionless, incompressible flow. The conservative upper limits (applicable to large particles that do not respond in any way to the air motion, but are simply swept into the engine by geometric interception; actual errors will be less than these figures) to exaggeration or underestimation of the CWC so estimated were an exaggeration of 20%–25% at an airspeed of 150 m s^{-1}, and an underestimation of the same order at 100 m s^{-1}. The proper speed for isokinetic sampling was estimated to be 120 m s^{-1}, and, following the determination of that value of airspeed, it was set as the standard cloud-penetration speed. These estimates were made during test flights at 6000-m altitude. This aspect of the jet engine measurements merits further study.

It was not possible to check unequivocally the values given by the Lyman-alpha system because of lack of standards for comparison; however, in Morgan et al. (1989), it was shown that peak total water mixing ratio estimated from the Lyman-alpha system in clouds with low 2D-C particle counts (less than 10 L^{-1}) tended to be at and below the adiabatic value (the cloud-base mixing ratio). That the cores of cumulus congestus clouds are often adiabatic was shown by Heymsfield et al. (1978) for Colorado clouds. It was also shown that, in the strong-echo ($\geq$40 dBZ) region of a cloud, the radar echo value Z measured by the digitized onboard X-band radar fell between the values calculated from the CWCs based on the upper and lower limits of the experimental Z–M data of Brown and Braham (1963) and the mass M derived from the engine instrument (the units of M were in grams per cubic meter, and M was the difference between CWC and the water content estimated by the King, which contributes insignificantly to the radar echo). The Lyman-alpha estimate of CWC was never less than the value of LWC from the King.

Ideally, a testing program would have involved flying in certain clear situations, such as in cloud regions without any precipitation (e.g., just above cloud base) or with purely water precipitation (as in rain shafts). Unfortunately, this testing was not done, because the aircraft was operated in a rigidly randomized program of cloud seeding, flying almost exclusively at and near the -10°C level (about 6000 m). All-water clouds (only clear droplet images visible to the 2D-C) are very infrequent at those temperatures, but, on one occasion in which this occurred, it was shown by Mather (1990) that the Lyman-alpha condensed water minus the cloud liquid water estimated by the King instrument agreed closely with the estimate of precipitation content calculated from the 2D-C data.

Perhaps the best support for the Lyman-alpha technique is the clarity and simplicity of its underlying physical principle. It was concluded that the Lyman-alpha technique gave reasonable estimates of the total and condensed water mixing ratios.

At the same time, a second, calorimetric, technique was taken under development, based on measuring changes in potential temperature of air exiting the last compressor stage. Water and ice that enter the engine intake are melted and evaporated in the compressor, causing a cooling of the air in the engine below the temperatures experienced during flight in clear air. The cooling is related through very simple thermodynamic principles to the amount of condensate evaporated. The measurement of temperature and pressure takes place in a tube just outside the main engine housing, where the air is expanding away from the eighth compression stage, so that the temperatures and pressures measured are lower, to an unknown degree, than those that occur at the eighth compression stage.

3. The calorimetric instrumentation

The aircraft employed in the cloud research is a Learjet 24 (Fig. 1) with General Electric, Inc., CJ-610 turbojet engines. Figure 2 shows a cutaway view of such an engine. During a cloud run, air enters the engine from the left of the figure at a speed near 110–160 m s^{-1}. The first section it encounters is the compressor, composed of eight annular, rotating (about 12 000 rpm) stages, which compresses the air by about a factor of 5. This compression raises the temperature of the air (at the point of measurement) from near -10°C to nearly 300°C and its pressure from near 500 hPa to 2500–3000 hPa. Sensors of temperature and pressure have been mounted inside a utility air outlet located aft of the last (eighth) compressor stage of the port engine, indicated in Fig. 2. The temperature in the engine is sensed with a Type-''J'' iron–constantan junction with integrated conditioning and amplification; the maximum error to be expected in measuring a constant temperature with this instrument is 0.2°C (this error translates into an error of 0.15 K in engine potential temperature and 0.08 g kg^{-1} in calculated CWC, a very small error when com-

FIG. 1. The cloud physics Learjet being prepared for a flight from its base at Nelspruit, South Africa.

pared with other uncertainties in the measurement). The response time of this temperature-sensing system was roughly estimated on the laboratory bench as being less than 1 s. The pressure is sensed with a Wika type-892 membrane sensor. It has a maximum error of 4 hPa, which would lead to an error of less than 0.05 K in engine potential temperature and hence less than 0.03 g kg^{-1} in calculated CWC. The manufacturer gives the 63% response time of the pressure sensor as less than 25 ms, which is virtually instantaneous, relative to the 10-Hz sampling rate of the airborne data system. The outside air temperature is sensed with the widely used Rosemount Model-102 platinum resistance sensor, which has a range of $-50°$ to 50°C and a maximum

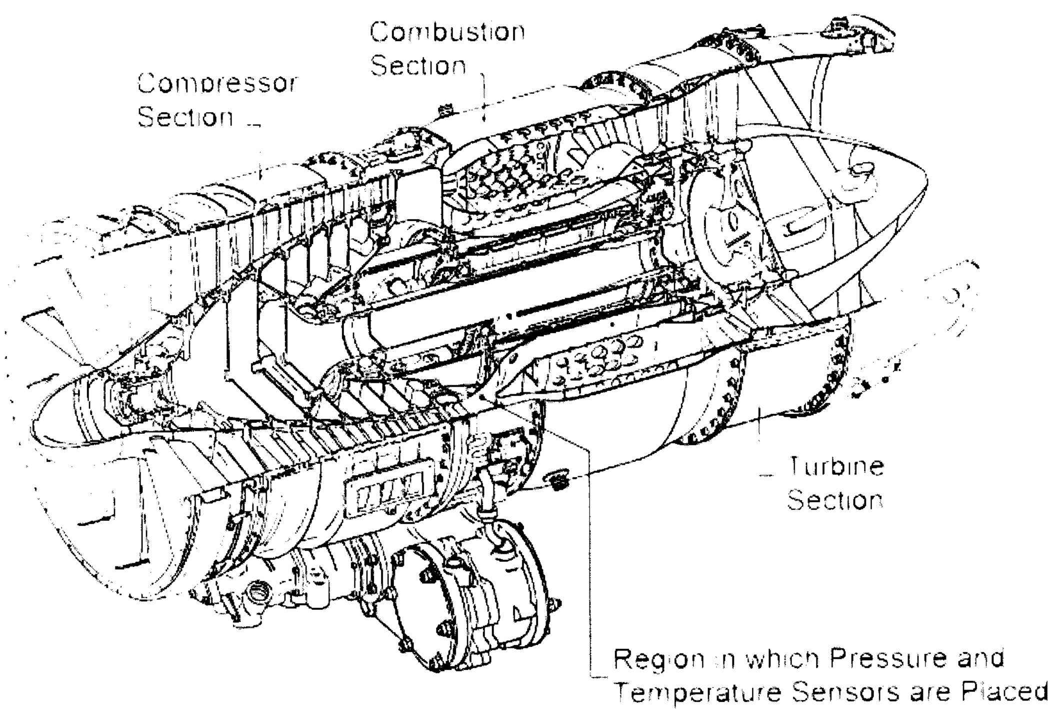

FIG. 2. Cutaway view of the General Electric, Inc., CJ-610 turbojet engine, showing its principal parts and the point from which air is drawn for the calorimetric estimation of condensed water content in clouds.

error in dry conditions of 0.5°C (and hence a possible 0.2 g kg^{-1} error in CWC). Wetting of the sensor in clouds can lead to additional error as large as 1.0°C (this wetting would appear to be the largest potential source of error in the system and could produce an error of 0.4 g kg^{-1} in CWC). The free-air static pressure is measured with a Rosemount Model-1201F1 temperature-compensated capacitor sensor with a range of 0–1000 hPa, a response time of less than 25 ms, and a maximum error of 1.0 hPa. The signals from all instruments are fed into a 16-bit analog-to-digital converter; noise levels measured are confined to the lowest two bits, so the system noise is very low. The sensors are read each 0.1 s, and signals are recorded on magnetic tape.

4. The measurement technique

Dry air entering the engine compressor at outside pressure P_a and temperature T_a (and hence potential temperature θ_a which is continuously calculated from them, in and out of cloud) undergoes compression and heating. The heating is mostly adiabatic but is also in part derived in some way from the engine. At the point of measurement behind the engine compressor, one finds that the potential temperature during flight in clear air is

$$\theta_c = \theta_a + \Delta\theta, \tag{1}$$

where $\Delta\theta$ is the increase in potential temperature from heating by the engine. Here $\Delta\theta$ is a function of engine performance. It can be evaluated by flying at different altitudes and power settings. In fact, in analyzing data from research flights, it can be evaluated at the beginning of each cloud run after the aircraft has been stabilized for cloud penetration. The mechanism for this heating is not known, but it could come from several sources: infrared radiation, mechanical heating, and conduction from the engine's surfaces. This diabatic contribution to the potential temperature is assumed to be constant at all times during the cloud run.

Changes in pressure in the engine during cloud runs are minor and primarily are due to changes in true airspeed and altitude in response to turbulence and drafts. In cloud air, there will be an additional change in θ_c from the evaporation of the condensed water $\Delta\theta_{\text{cond}}$ such that

$$\theta_c = \theta_a + \Delta\theta - \Delta\theta_{\text{cond}}. \tag{2}$$

Here $\Delta\theta_{\text{cond}}$ can be specified as a function of the mixing ratio of condensed water in the air, as follows: the evaporation of an amount dw_l of liquid water into a kilogram of air results in a temperature change

$$dT = -L_e\, dw_l/c_p \tag{3}$$

and, consequently, a potential temperature change

$$\begin{aligned} d\theta &= -(1000/P)^{0.286}\, dT \\ &= -(1000/P)^{0.286} L_e\, d(w_l)/c_p, \end{aligned} \tag{4}$$

where P is the engine pressure, L_e is the latent heat of evaporation of water, and c_p is the specific heat of dry air at constant pressure.

Similar equations hold for the sublimation (or melting followed by evaporation) of ice with the latent heat of sublimation L_s and the ice mixing ratio w_i taking the place of the latent heat of evaporation and the liquid water mixing ratio. We do not have information about all stages of this complex process. It is not possible to know the temperature at which the water is evaporated in the engine; we only know that any ice present will melt at 0°C. In proceeding with this development, we always assume that $L = 2500$ J g^{-1}, its all-water value at 0°C. Assuming the cloud to be composed of ice only, and hence the relevant latent heat to be 2834 J g^{-1}, would, in view of Eq. (8), below, result in a reduction of 12% in the inferred CWC. Alternatively, assuming the condensate to be entirely liquid, and the evaporation to occur at 50°C, would require a 5% reduction in L and a very slightly smaller increase in the inferred CWC.

The possibility must be considered that particles striking the static and rotating stages of the compressor might exchange heat with them and introduce errors with respect to our analysis. This possibility would be exceedingly difficult to determine, but we take the good agreement between the calorimetric and the vapor extinction techniques to suggest that such errors, if they exist, are not serious. This effect could bear further analysis.

The first attempts to perform this measurement are reported in WRC (1986). These measurements showed that something was missing in the analysis. The potential temperature in the engine appeared to return slowly to its original, clear-air value after leaving the cloud, and the profiles of CWC were not similar to those based on the vapor content measurement. A simple accounting for the time response of the temperature measurement in making the calculations seems to have largely solved the problem.

First, a first-order correction of the engine temperature versus time is performed, with

$$T_{\text{corr}} = T + (1/K)\, dT/dt, \tag{5}$$

in which t is time, and K is an empirical constant determined (for a set of cloud penetrations) in the moments (3 s) following exit from cloud, using

$$K = [1/(T_0 - T)]\, dT/dt, \tag{6}$$

where T_0 is the temperature just prior to cloud entry. Note that the inverse of K is the conventional 1/e time constant for an exponentially decaying function. The value of K was found to be 0.35, which corresponds to about a 3-s time constant. This result, when confronted with the purely instrumental time constant of less than 1s, indicates that the overall response contains effects from the sensor, the engine, and the region in which the measurement is made. We have speculated that the major source of sluggishness in the temperature measure-

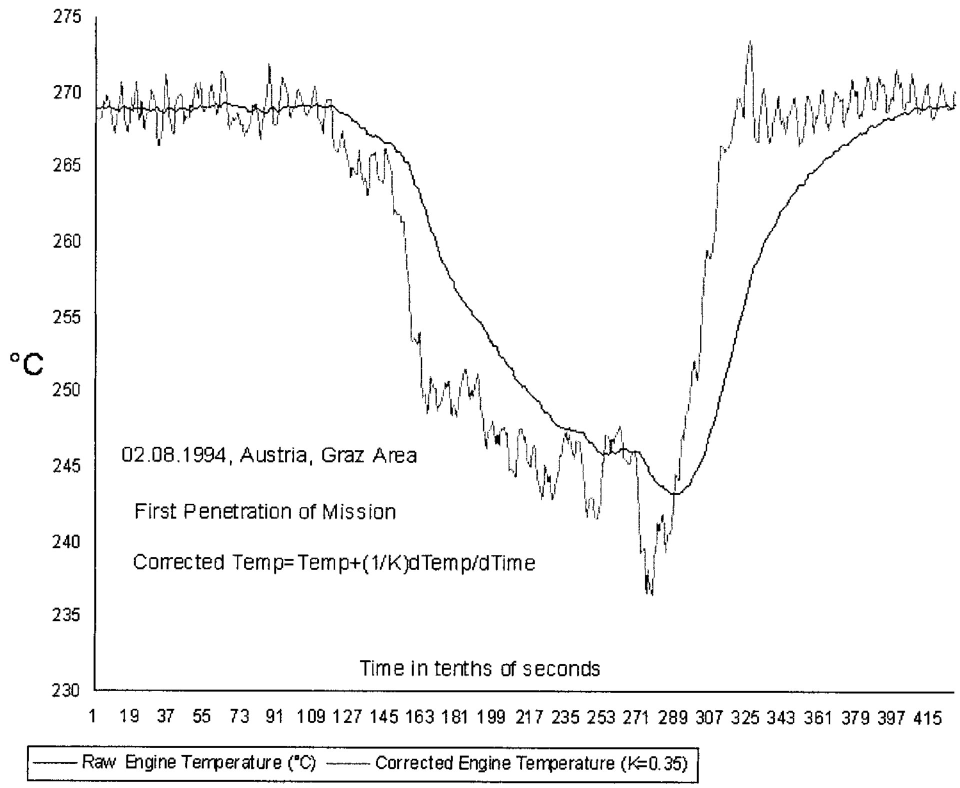

FIG. 3. An example of the raw engine temperature and the corrected engine temperature, as described in the text, for a cloud encountered near Graz, Austria, on 2 Aug 1994.

ment may be in the tubing walls in the immediate vicinity of the thermocouple—possibly a radiation effect. Figure 3 shows an example of the engine temperature versus time and the corresponding corrected engine temperature. Note the noise induced by the differencing. This noise can be modified by varying the interval (3 s in this case) over which the derivative is estimated and/or filtering the corrected temperature. In our field work, this noise has not been considered to be important, and no smoothing has been applied to the measurement.

Next, the potential temperature in the engine is calculated using the corrected engine temperature. The outside air temperature and pressure are used to calculate the environmental potential temperature. The difference between the potential temperature in the engine and that in the outside air, $\Delta\theta$, is then calculated over the run, and an average of that difference, $\Delta\theta_0$, is calculated over a time interval prior to cloud entry. This average is a measure of the diabatic heating, which takes place in the engine, and is subtracted from the difference over the rest of the run to yield the cooling effect of the condensate. Implicit here is the assumption that this contribution to the potential temperature of the air in the engine is *constant* throughout the time the aircraft is in cloud. There is no way to verify this assumption, but the reasonableness of the final results suggests that it is approximately correct. The condensed water mixing ratio CW is then given by

$$\mathrm{CW} = -(\Delta\theta - \Delta\theta_0)(c_p/L_e)/(1000/P)^{0.286}. \qquad (7)$$

An example is given in Fig. 4, with the CW estimate from the Lyman-alpha technique also shown. The cloud shown for demonstration here was a moderately strong cumulus congestus cell encountered near Graz, Austria, on 2 August 1994, at -11°C. Cloud width was approximately 2.5 km. The 2D-C recording made in this cloud showed low (a little above 10 L^{-1}) concentrations of particles at the edges of the cloud and very low particle concentration in the core of the updraft, a recurrent pattern in growing cells. The maximum updraft speed was over 20 m s^{-1}. Detailed differences between the curves are due to the differing sources of error of the two techniques, (probably varying) time response differences, and timing delays caused by the physical distance between the relevant sensors (the engine pressure and temperature sensors are located on the engine; the Lyman-alpha sensor system is located in a utility air line, remote from the engine).

It is not possible to make short-time comparisons between the two instruments, because there are time delays between them that are not fully understood and may not be constant. The Lyman-alpha technique involves long

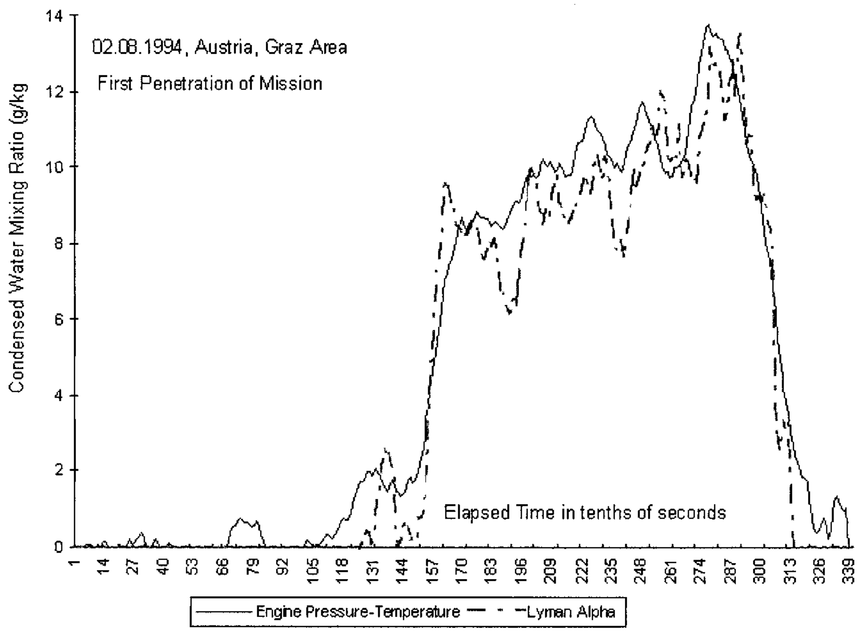

FIG. 4. An example of calorimetric and optical extinction estimates of condensed water content (g kg^{-1}), as a function of elapsed time (in tenths of seconds) during a cloud penetration. This cloud was encountered near Graz, Austria, on 2 Aug 1994, at a temperature of −11°C and altitude 5600 m.

runs of tubing, and the calorimetric technique does not. Also, the Lyman-alpha technique takes air from both engines, but the calorimetric technique takes air from only one, which can create differences over very short time spans as the aircraft yaws and pitches. We do not feel this possibility compromises the value of the measurement. Figure 5 shows a comparison between the cloud-average estimates of condensed water mixing ratio by the two methods for 56 clouds from the 1994 measurement campaign in Friuli, Austria, and Croatia. The agreement between the two estimates of condensed water mixing ratio is excellent for airborne measurements of this kind. The scatter shown can be attributed largely to errors in the baselining of the Lyman-alpha instrument. The fact that two estimates of the CWC based on completely different physical principles agree to the extent shown argues that the estimates are not grossly in error. It also argues against any significant variations in the diabatic heating, estimated in clear air, while the aircraft is in clouds. The small values of the partial errors from the various sensors involved lead us informally and conservatively to estimate the overall maximum error of the technique at less than 1.0 g kg^{-1}. Of particular importance in judging the results of cloud penetrations with this instrumentation is evaluation of the state of the aircraft prior to and during the run. The power setting (rpm) must be stabilized, the aircraft must have been in level flight, and excessive airspeed fluctuations must be flagged.

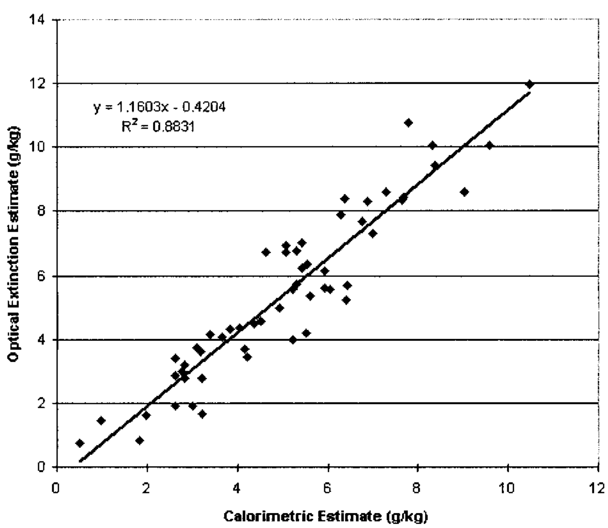

FIG. 5. Comparison of average condensed water content estimated by the calorimetric and optical absorption methods in 56 clouds from the 1994 measurement campaign in Friuli, Austria, and Croatia.

5. Summary comments

Estimation of condensed water mixing ratio by the jet engine techniques is simple and relatively inexpensive. Sample volumes are very large, around 15 $m^3 s^{-1}$ per engine, and the Learjet can fly in conditions prohibitive for most other research aircraft. With these techniques, it has been possible to make unprecedented measurements of high water contents in cumulus clouds (Morgan et al. 1989; Mather 1990). Comparisons between the condensed water mixing ratio calculated from Lyman-alpha extinction and from the engine temperature technique show that these independent measures are highly correlated. The current technique is particularly convenient in that it does not involve sophisticated sensors. We believe that it is superior to the Lyman-alpha technique in that it does not require baselining against a humidity measurement. This new measurement technique requires circumspection in evaluating the veracity of its estimates, as do all in-cloud, airborne instruments.

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REFERENCES

Ackerman, B., 1974: The partition of liquid water near the freezing level. Preprints, *Conf. on Cloud Physics,* Tucson, AZ, Amer. Meteor. Soc., 300–327.

——, and N. E. Wescott, 1986: Midwestern convective-clouds, a review. *J. Wea. Mod.,* **18,** 87–93.

Baumgardner, D., and J. E. Dye, 1982: Cloud Particle Measurement Symposium: Summaries and abstracts. NCAR Tech. Note NCAR/TN-199 + PROC, 103 pp. [Available from UCAR Communications, P.O. Box 3000, Boulder, CO 80307-3000.]

Biter, C. J., J. E. Dye, D. Huffman, and W. D. King, 1987: The dropsize response of the CSIRO liquid water probe. *J. Atmos. Oceanic Technol.,* **4,** 359–367.

Brown, E. N., and R. R. Braham, 1963: Precipitation particle measurements in cumulus congestus. *J. Atmos Sci.,* **20,** 23–28.

Coulman, C. E., and M. A. Parker, 1982: On the calibration and performance of an instrument for measuring total water mixing ratio in cloud. *J. Appl. Meteor.,* **21,** 695–702.

Gayet, J. F., M. Friedlander, and J. P. Pinty, 1977: Sur la mesure de la teneur en eau totale des nuages (On the measurement of the total water content of clouds). Sci. Rep. 22, 26 pp. [Available from Lab. Assoc. Meteor. Phys., Université Blaise Pascal/CNRS/OPGC, 24 avenue des Laudais, F-63177 Aubiere CEDEX, France.]

Heymsfield, A. J., P. N. Johnson, and J. E. Dye, 1978: Observations of moist adiabatic ascent in northeast Colorado cumulus congestus clouds. *J. Atmos Sci.,* **35,** 1689–1703.

Kyle, T. G., 1975: The measurement of water content by an evaporator. *J. Appl. Meteor.,* **14,** 327–332.

Mather, G. K., 1990: Evidence of an accumulation or ''big drop'' zone. *Bull. Amer. Meteor. Soc.,* **71,** 345–348.

Morgan, G., 1992: The problem of the measurement of water quantities in cumulus clouds. *Proc. WMO Workshop on Cloud Microphysics and Applications to Global Change,* Toronto, ON, Canada, WMO Rep. 19, 121–125.

——, and G. K. Mather, 1984: Problems in the measurements of liquid water content in Transvaal clouds. *Extended Abstracts, Ninth Conf. on Weather Modification,* Park City, UT, Amer. Meteor. Soc., 24.

——, B. J. Morrison, and G. K. Mather, 1989: Measurement of total and condensed water mixing ratios in warm-based cumulus clouds by a jet engine evaporation technique. *Theor. Appl. Climatol.,* **40,** 187–199.

Roys, G. P., 1963: Airborne instrumentation system for measuring meteorological phenomena inside thunderstorms. Tech. Doc. ASD-TDR-63-231, 59 pp. [Available from Directorate of Flight Test, Aeron. Systems Div., Air Force Systems Command, Wright–Patterson AFB, Ohio, 45433-9907.]

——, and E. Kessler, 1966: Measurement by aircraft of condensed water in Great Plains thunderstorms. Tech. Note 49-NSSP-19, 17 pp. [Available from NOAA/National Severe Storms Lab., 1313 Halley Circle, Norman, OK 73069.]

Ruskin, R. E., and W. D. Scott, 1974: Weather modification instruments and their use. *Weather and Climate Modification,* W. N. Hess, Ed., John Wiley and Sons, 136–205.

Smith, P. L., Jr., 1976: Comments on the measurement of water content by an evaporator. *J. Appl. Meteor.,* **15,** 189–191.

WRC, 1986: Program for Atmospheric Water Supply, Phase 1, 1983–1986. Vol 4: Instruments, techniques and studies. Report to the Water Research Commission by Simpson Weather Associates and Cansas International Corporation. WRC Rep. 133/4/88, 336 pp. [Available from Water Research Commission, P.O. Box 824, Pretoria 0001, South Africa.]