A Frost-Point Hygrometer for Horizontal Soundings of the Lower Stratosphere

M. ROULLEAU AND M. M. POC

Laboratoire de Météorologie Dynamique du C.N.R.S., Ecole Polytechnique, 91128 Palaiseau Cedex, France

(Manuscript received 4 November 1977, in final form 4 February 1978)

ABSTRACT

A new kind of frost-point hygrometer has been developed for horizontal soundings of the lower stratosphere. The cooling source, using the radiative cooling of a blackbody during the night, is able to cool the mirror down to −90°C. The frost deposit is detected with an optical sensing unit associated with a regulating loop controlling the mirror heating to keep the frost thickness constant. The equipment is presented and described and the results of the first flight performed in 1976 are given and discussed.

1. Introduction

The knowledge of the water vapor mean concentration in the lower stratosphere and its variability is of obvious interest to meteorology, especially if water vapor is regarded as a tracer of large-scale stratospheric circulation and of tropospheric-stratospheric exchanges.

The most recent review of the measurements of stratospheric humidity was made by Harries (1976). To summarize, up to 30 km, hygrometric measurements in flight have shown 1) a rapid decrease of humidity at the tropopause level; 2) a mixing ratio value roughly constant above 20 km, about 2.5×10^{-6} (Mastenbrook, 1968); 3) a seasonal trend of this value in the Northern Hemisphere; lowest mixing ratios are encountered during late winter and highest mixing ratios during late summer; and 4) a long-term increasing trend since 1964; the mixing ratio increased from 2–3 parts per million (ppm) over a six-year interval (Mastenbrook, 1971).

The various assumptions suggested concerning sources and sinks of stratospheric water vapor have been reviewed by Weickmann and Van Valin (1972). According to Dobson *et al.* (1946) and to Brewer (1949), the mean meridional circulation could explain the roughly constant value of the mixing ratio above 20 km. Such dry air might enter the equatorial lower stratosphere through large cumulonimbi whose higher parts overcome the tropopause level. These parts can be colder than ambient because of the adiabatic cooling due to the ascending motion. This air entering the stratosphere can reach temperatures as low as −91°C. This dry air is nearly saturated with respect to ice with a mixing ratio lower than 10^{-6}. An interesting correlation seems to exist between the seasonal variation of the temperature of the equatorial tropopause and the magnitude and seasonal variation of the mixing ratio in the lower stratosphere.

Since Brewer and Dobson's studies, recent investigations suggest some other sources of stratospheric water vapor. First, mean ascending motions are found in the winter stratosphere over the North Pole where tropopause temperatures are considerably higher than over the equator. An amount of water vapor, higher than that allowed for by the Brewer-Dobson model, may seep into the stratosphere (Vincent, 1968). Second, eddy-transport processes, in conjunction with pronounced polar front or subtropical jet maxima, may cause considerable inflow of moist tropospheric air into the stratosphere (Reiter, 1971; Smith, 1968).

In contrast to these several possibilities for sources, fewer serious possibilities for sinks of stratospheric water vapor have been proposed. One possible sink involves the gradual diffusion of water vapor upward in the atmosphere; at high levels, radiation breaks up the H_2O molecule into hydrogen and oxygen. A second possible sink involves intrusions of stratospheric air down into the troposphere. But, because of the accompanying upward intrusion into the stratosphere of a mass of presumably moister tropospheric air, the net effect could be either a source or a sink. Finally, according to Stanford (1973), because temperatures in the winter antarctic lower stratosphere often reach as low as −90°C, the water vapor may condense and ice particles can grow large enough to fall down to tropospheric levels. A sink might then exist, where part of the stratospheric water vapor content disappears.

In order to examine the validity of these various theories, a great number of measurements of strato-

0021-8952/78/0803-0811$05.00

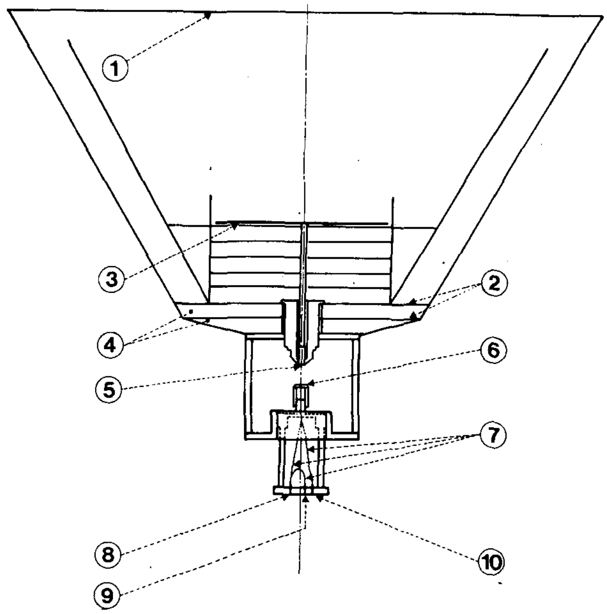

FIG. 1. Schematic diagram of the frost-point hygrometer: (1) polyethylene, (2) cones, (3) black plate, (4) polystyrene, (5) mirror, (6) lens, (7) optical fibers, (8) emission diode, (9) measuring phototransistor, (10) reference phototransistor.

spheric water vapor content is required. For this purpose we intend to make horizontal soundings with constant-level balloons at the 100 mb level. This technique of investigation provides a means of collecting a great deal of data. The real distribution of water vapor content and its natural variation at a given level of the lower stratosphere in a whole hemisphere could be obtained with the same instrumentation. Thus, it might be possible to avoid the uncertainties which appear in the comparisons between values derived from various experimental processes. Moreover, contamination is a difficult problem for *in situ* measurements by balloon. Long time flights with constant-level balloons help to solve this problem. Indeed, there will be no contamination by the balloon in horizontal soundings and, after some time, perhaps a few days, moisture desorption from the instrumentation will be complete.

2. Instrumentation

The initial objective of the program was to develop an instrument able to support the stresses inherent in the horizontal sounding technique; in particular, the apparatus must be light-weight, economical, and able to work with minimum energy consumption. Moreover, the balloon borne apparatus must be sufficiently accurate to measure a very small quantity of water (10^{-6} g g^{-1}) and also must be reliable, because it must work without drift during several months. To meet these requirements, the frost-point hygrometer has been selected. The frost-point principle is well known. Air whose frost point is required is passed over a clean mirror which can be cooled and whose temperature can be measured. The frost point is taken to be the temperature at which a small trace of frost remains on the mirror without increasing or decreasing in amount. Although based on a principle which seems easy and theoretically accurate, the development of a frost-point hygrometer designed for measuring frost points down to −80°C is rather complex.

The frost-point hygrometer built in our laboratory consists of 1) a cooling source, 2) a mirror of polished aluminum for optical detection, 3) a resistance wire heater wound round the mirror to control its temperature, 4) an optical sensing unit for detecting changes in the deposit thickness, and 5) a device for measuring the mirror temperature. These various parts of the apparatus have been developed by means of laboratory tests and preliminary flight tests.

a. The cooling source

Generally, dew- or frost-point hygrometers employ one of two techniques for controlling the temperature of the mirror. In the first, low temperatures are obtained by immersing a rod in a fluid that has a low boiling point, and a resistance heater, wound on the rod under the mirror, is used to control the mirror temperature by supplying heat to the rod. In the second, thermoelectric elements are used to control the temperature of the mirror. Neither of these techniques can be used for horizontal soundings because the cooling system has to operate for several months using minimum energy. Thus we have built a cooling source which uses the radiative cooling of a blackbody during the night (Trombe *et al.*, 1964, 1974). The cooling source is shown in Fig. 1. The blackbody is an 11 cm diameter copper plate painted with Parsons Optical Black lacquer, connected to the mirror with a rod of the same metal. A calibrated thermistor, embedded under the surface of the mirror, senses its temperature which is controlled by heat supplied by a resistance wire heater wound round the mirror.

At 100 mb, the frost-point temperature is about −80°C. The mirror surface must be cooled to a lower temperature to insure the necessary supersaturation. Thus a relationship between the maximum cooling of the mirror and the heat necessary to maintain the frost thickness constant is required which will minimize the electric power used in the resistance. A cone of aluminized mylar shields the black plate from the effects of wind and terrestrial radiation. A second cone, inside the first one, further reduces effects due to air motion. Alternately arranged polystyrene and aluminized mylar layers ensure thermal insulation under the plate. A 25 μm thick polyethylene film is stretched on the upper part of the first cone to reduce convection and turbulence of air above the plate.

Polyethylene has a good transmission in the atmospheric infrared emission range—between 85 and 90% for a thickness of 25 μm.

Balloon flight tests, carried out in tropical latitudes, have shown that the cooling of the mirror is at least 20°C below the ambient. Indeed, the temperature of the mirror is about −90°C when the ambient is about −70°C. Furthermore, 1 W of electric power dissipated in the heating resistance increases the mirror temperature up to −75°C. Thus, the range of mirror temperatures more than covers the frost-point temperature value of −80°C.

b. Detection of the frost deposit and ventilation of the mirror

The frost deposit is detected by illuminating the mirror at normal incidence with an infrared light source (a gallium-arsenide light-emitting diode) which is associated with a cylindrical rod of glass fibers. The light reflected by the mirror is conducted through another rod of glass fibers and falls on a measuring phototransistor. A part of the emitted light flux is conducted through a third rod of glass fibers toward a second reference phototransistor.

The geometrical form of the sensing unit (Fig. 1) has been designed so as to avoid interference with the air flow and to obtain a suitable ventilation of the mirror. This ventilation is due only to the vertical wind sheer, which is of the order of 1–2 m s^{-1} when the apparatus is hung 100 m below the balloon (Cadet, 1973). Attached to the front of the glass fibers is a lens having a focal length of 8 mm and a diameter of 7 mm; the lens-mirror distance may vary from 1 to 2.5 cm. The sensing unit is centered opposite to the mirror with a plate fixed on the bottom of the cooling source by means of three little columns spaced as far apart as possible (34 mm from the center of the mirror).

Some measurements were made in a low-speed wind tunnel in order to determine the air velocity V_M at the mirror versus the velocity of the air flow V_∞. The stratospheric nacelle was hung in the jet of the wind tunnel. The air velocity at the mirror was measured with a calibrated thermistor set 1.5 mm below the mirror. The sensing unit was set in two different positions with respect to the flow: first (the best one) with one little column directly downstream from the mirror, and second (the worst one) with one little column directly upstream from the mirror. Fig. 2 shows V_M vs V_∞ for these two positions. With V_∞ varying from 1 to 2 m s^{-1}, for the first position V_M varied from 1.30 to 2.75 m s^{-1}, while for the second position V_M varied from 0.90 to 2.05 m s^{-1}. Thus, whatever the sensing unit position in the flow, the wind speed at the mirror is at least of the order of the wind speed in the air flow.

The variation of mirror temperature with wind velocity has also been studied in the low-speed wind tunnel. The experiments could not be done at negative temperatures, however, because a thick layer of frost would condense on the mirror, forming a thermal insulator which would disturb the measurements. Therefore, to make these measurements a positive temperature gradient between the plate of the cooling source and the mirror has been established by using a heating resistance set under the plate. The plate temperature was measured with a calibrated thermistor. A control system maintained this temperature constant to ±2.5°C. With an ambient temperature of about +20°C, the plate was heated up to about +50°C in order to have a plate-air temperature difference of the same order of magnitude as that in the stratosphere. Experiments were made by hanging the nacelle in the jet of the wind tunnel, with the sensing unit being in the best position for the flow. Fig. 3 shows that, for a wind speed of 1–2 m s^{-1} at the mirror, the variation of the mirror temperature due to the wind is about 1°C.

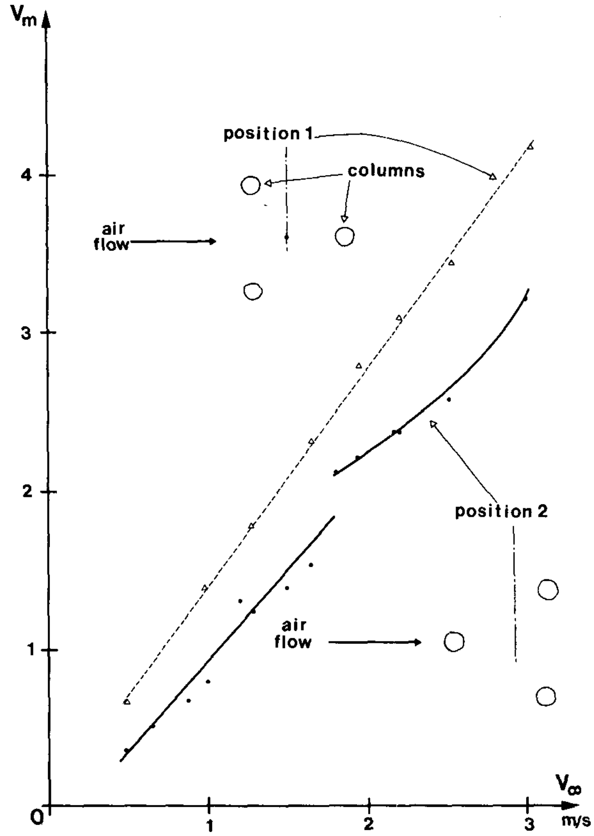

Fig. 2. Air velocity V_M at the mirror versus air velocity V_∞ of the flow in the wind tunnel.

c. Regulation of the mirror temperature

This regulation, intended to keep the frost thickness constant, is based on the difference between the output

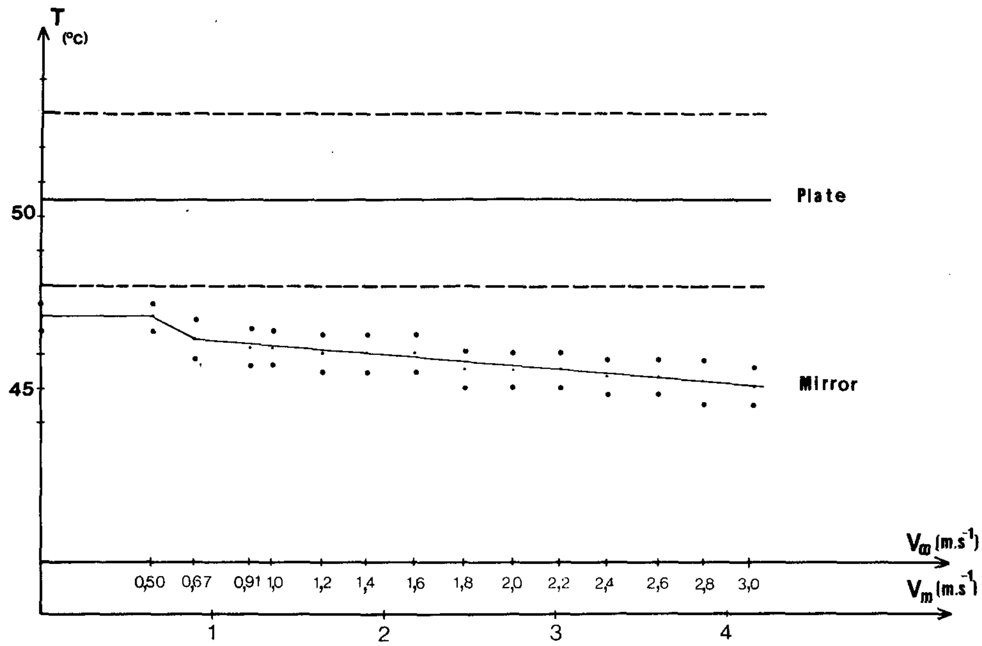

FIG. 3. Influence of wind on the mirror temperature.

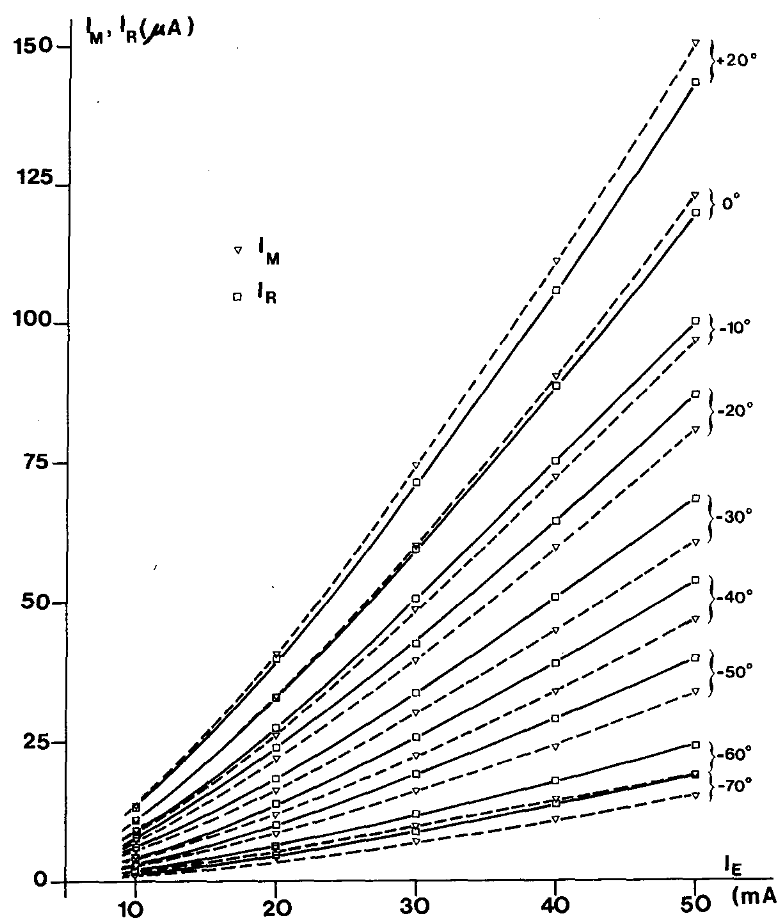

FIG. 4. Phototransistor currents versus the diode current at different temperatures.

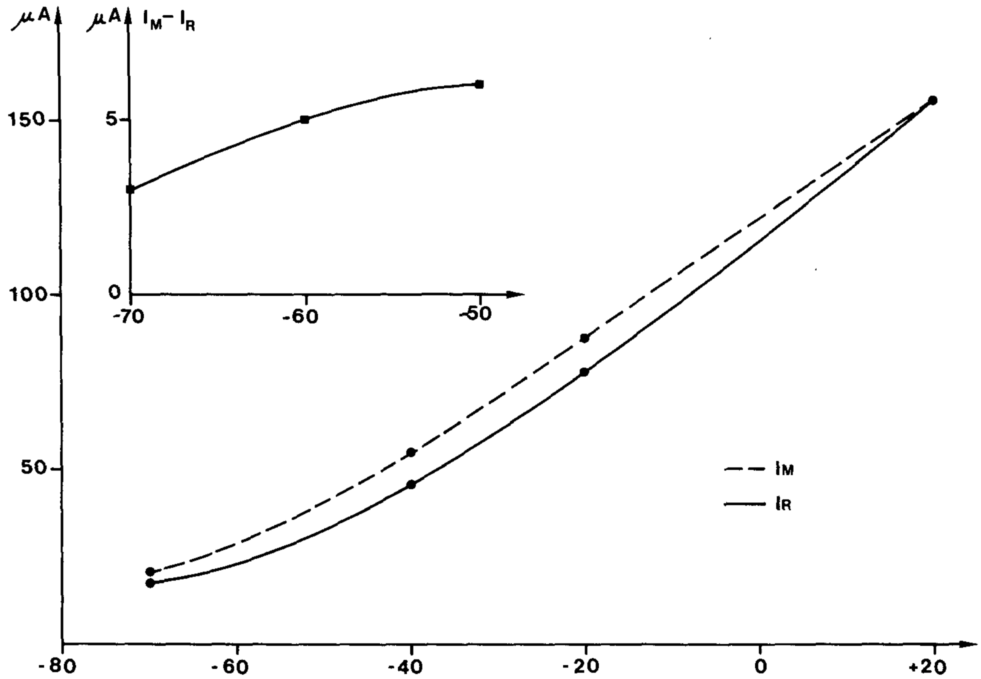

FIG. 5. Temperature variation of I_M and I_R and of the difference I_M-I_R.

currents of the phototransistors when the light received by the measuring phototransistor is attenuated by the frost. At various temperatures Fig. 4 shows the variations of the phototransistors' currents I_M and I_R versus the diode current I_E. To obtain about 20 μA, with an ambient of -60°C, I_E must be equal to 50 mA. For this value, temperature drifts for I_M and I_R have been measured. The I_R value is fixed by the position of the reference phototransistor in front of the associated glass fiber. I_M is then made equal to I_R by varying the mirror-detector distance. Fig. 5 shows the variation of I_M and I_R and the variation of the difference $\delta(I_M-I_R)$ with temperature. For a 5°C temperature variation around -60°C, the $\delta(I_M-I_R)$ variation stays lower than 1 μA. During the flight, at the ceiling altitude, the air temperature is constant at about ±2°C. Thus, the difference $\delta(I_M-I_R)$ due to the temperature drifts can be considered as a constant during the flight. Fig. 6 shows the principle of the apparatus. When there is a frost deposit on the mirror, I_M varies several μA while the reference current I_R stays constant. The difference between the two currents due to the frost is used as signal to the regulator loop for the mirror heating. During the flight, the value of the heating power is telemetered to monitor the behavior of the hygrometer. To avoid having a difference $\delta(I_M-I_R)$ due to the temperature drifts (which are unknown before the frost deposition), initialization of the system is achieved by equipping the reference phototransistor with a

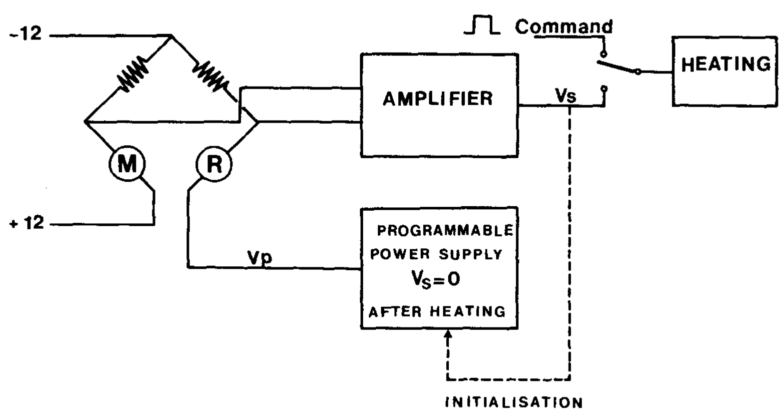

FIG. 6. Principle of the apparatus.

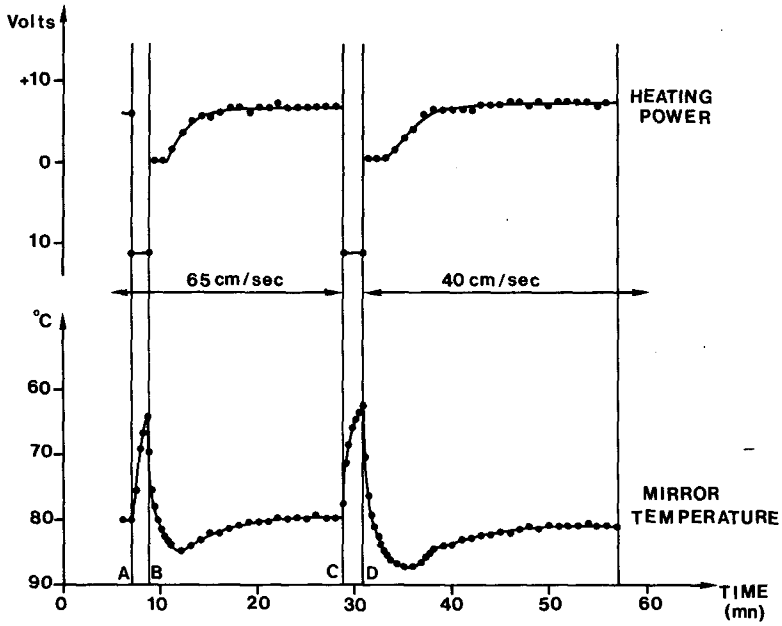

FIG. 7. Laboratory tests with two different air velocities.

programmable power supply which sets the heating power equal to zero when there is no frost on the mirror.

3. Laboratory tests

The hygrometer was tested in the laboratory using the calibration device developed by Ovarlez-Fourier (1971) which consists of an air circulation in closed circuit. First, air passes into a saturator at a given temperature, then into a test chamber whose temperature is higher than the saturator temperature. The detector, previously adjusted to have $I_M = I_R$, is set in the front of a mirror in the test chamber whose temperature is then cooled down to $-60°C$, when the air flow is saturated at about $-80°C$. The mirror is cooled down to temperatures lower than $-80°C$ by means of a cooling device using liquid nitrogen. The electronic system associated with the hygrometer is also in an ambient temperature of $-60°C$. Experiments are carried out with various air stream velocities. Calibration of air speed in the test chamber, measured at the output of the circulation tube, is made as a function of the flow. The air speed at the mirror is unknown but it is significantly lower than the air speed at the output of the tube because of the broadening of the pipe. Fig. 7 shows results of hygrometer tests obtained with two different air velocities. The upper curve shows the time variations of the values of the heating power on the mirror, and the lower curve indicates the temperature of the mirror. In A and C, the maximum heating is applied to eliminate all the frost which could have appeared during the cooling of the mirror, and to establish the zero of the apparatus. At points B and D the heating is switched off. The mirror is then rapidly cooled and, as soon as the frost appears, the heating slowly increases up to an equilibrium value which is determined by the regulator. The mirror temperature is measured to $\pm 0.3°C$. The accuracy of the frost-point temperature depends mainly on the accuracy of the definition of the thermal equilibrium of the mirror. From Fig. 7, this equilibrium can be defined to $\pm 0.5°C$; thus the frost-point temperature is known within about 1°C, giving an accuracy of 1 ppm for the mixing ratio under lower stratosphere conditions.

a. Response time

The response time of the hygrometer, or the time necessary to reach equilibrium, has been studied in the test chamber in the following manner: after the hygrometer has come to equilibrium at a frost point temperature of about $-80°C$, the heating of the mirror is cut off and the time required to obtain a new equilibrium is measured.

Each hygrometer has its own response time because of the influence of certain factors which are special for each apparatus (e.g., the characteristics of the light-emitting diode, the position of the lens or the position of glass fibers). However, other parameters are more important for the response time:

1) The value of the diode current (the higher the diode current, the faster is the reaction of the hygrometer).

2) The air velocity at the mirror. Fig. 8 shows the variation of the response time versus the air velocity.

The instrument responds more quickly if the mirror is properly ventilated.

3) The difference $T_D - T_M$ between the frost-point temperature and the maximum cooling temperature of the mirror. Fig. 9 shows a part of recording of the mirror temperature of one hygrometer; the greater the difference $T_D - T_M$, the faster the response of the hygrometer.

For our instruments, the average response time is of the order of 5 min when the difference $T_D - T_M$ is of the order of 5°C.

b. Sensitivity

The amount of frost necessary to obtain equilibrium is a possible measure of the sensitivity of the apparatus. Unfortunately, we cannot experimentally measure the quantity in the laboratory, because the tests are done in closed circuit. However, it is possible to make an approximate calculation using, as Wylie *et al.* (1965) have done, Pohlausen's equations for laminar flow past a flat plate at uniform temperature. The heat transfer coefficient can be obtained from these equations. The mean mass transfer coefficient and mass transfer rate are deduced from the heat transfer coefficient. For fluids having a Prandtl number Pr>0.6, the mean heat transfer coefficient h is given by

$$h = 0.664(K/L)(\mathrm{Re})^{\frac{1}{2}}(\mathrm{Pr})^{\frac{1}{3}}, \qquad (1)$$

where K is the thermal conductivity of the fluid and L the plate length.

Because the humid air properties are pressure- and temperature-dependent, the Reynolds and Prandtl numbers are evaluated at standard pressure and at a mean temperature defined by (Eckert, 1963, p. 115)

$$T^* = T_s + 0.5\,(T_M - T_S), \qquad (2)$$

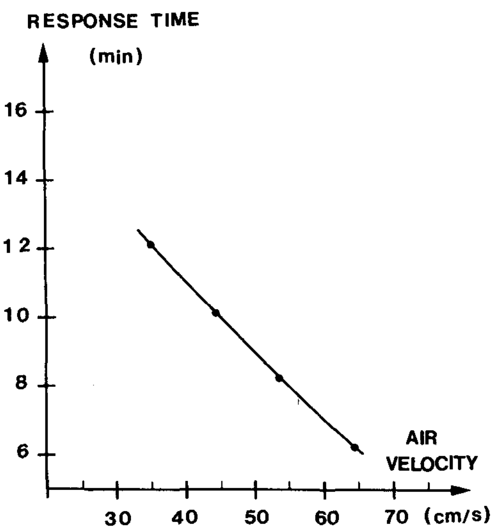

FIG. 8. Response time of the frost-point hygrometer versus the air velocity.

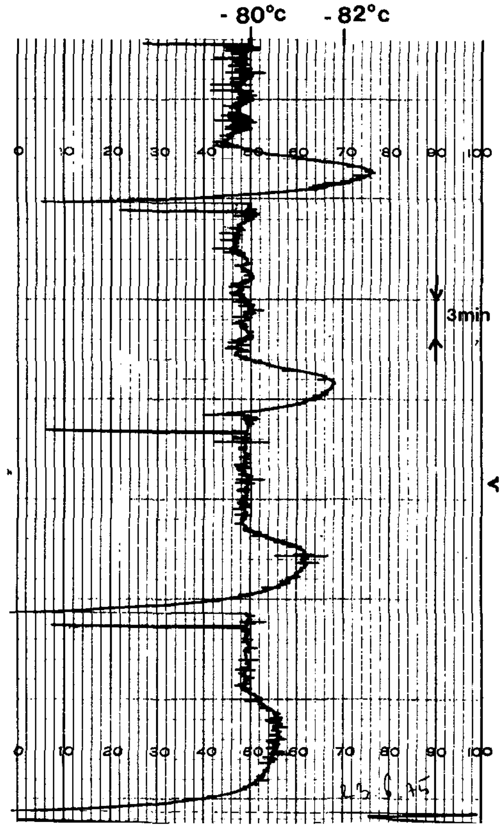

FIG. 9. Relationship between the response time of the apparatus and the difference $T_D - T_M$.

where T_s is the temperature of the flow at the edge of the boundary layer and T_M the mirror temperature. For our hygrometer in the laboratory tests

$T_s = -60$°C and $T_M = -85$°C with $T_D - T_M = 5$°C.

Taking the air velocity u_0 at the mirror to be 10 cm s^{-1}, we obtain

$$\mathrm{Re} = 53, \qquad \mathrm{Pr} = 0.74,$$

which gives

$$h = 4.7 \times 10^{-4} \text{ cal s}^{-1} \text{ cm}^{-2} \text{ (°C)}^{-1}. \qquad (3)$$

The analogy between heat and mass transfer allows one to define a mass tranfer coefficient for fluids having a Levis number of about unity which is the case for humid air at low temperatures (Eckert, 1963, pp. 284–285). The mean mass transfer coefficient h_m can be obtained from h using the expression

$$h_m = \frac{h}{c_p}. \qquad (4a)$$

The resulting value of h_m is

$$h_m = 1.9 \times 10^{-3} \text{ g s}^{-1} \text{ cm}^{-2}. \qquad (4b)$$

We can then use this coefficient to calculate the mass

RECORD NUMBERS	AIR TEMPERATURE °C	MIRROR TEMPERATURE °C	HEATING (VOLTS)
1	-68.4	-89.9	-10.5
2	-68.9	-74.6	+1
3	-69.8	-84.7	+2
4	-69.8	-87.3	+2.8
5	-69.8	-87.1	+4.4
6	-69.8	-85.1	+6.2
7	-71.0	-85.0	+5.6
8	-69.8	-83.9	+6.8

FIG. 10. Results of the flight of 10 December 1976.

transfer rate

$$\dot{m}=h_m\ (W_M-W_S). \qquad (5)$$

Here W_M and W_S are the saturating mass fraction of water vapor corresponding to T_M and T_S. Instead of W_S, we take W_S' the saturating mass fraction corresponding to $T_D=-80°C$, the saturation temperature of the air passing the mirror. We obtain

$$\dot{m}=4\times10^{-10}\ \mathrm{g\ cm^{-2}\ s^{-1}}. \qquad (6)$$

For the mean response time of 5 min with a difference $T_D-T_M=5°C$ and assuming that all the water is condensed on the mirror, the amount of frost deposit is

$$\Delta_m=10^{-7}\ \mathrm{g\ cm^{-2}}. \qquad (7)$$

Assuming a continuous layer on the mirror surface, this amount would correspond to a thickness of 0.1 μm, which is ten times higher than the Brewer's (1965) value for the same range of temperature. Of course, at these low temperatures, the deposit does not consist of a uniform layer but of spots growing from nucleation sites existing on the mirror surface.

4. Flight tests

One hygrometer has been launched from Pretoria with a 5.8 m diameter constant-level balloon. The ceiling altitude was the 100 mb level. The apparatus, hung 100 m below the balloon, weighed 1 kg and the maximum electric power necessary for the hygrometer and the telemetry was 2.5 W. The electric power was supplied to the hygrometer by batteries which can be recharged during the day by solar cells. Measurements were made during the night, and the data were put in memory and the measured parameters (air temperature, mirror temperature and heating value) were transmitted during the day. Only one set of measurements was made, consisting of eight successive records 15 min apart. Between the first and the second recording, maximum heating was applied to the mirror to eliminate the frost and establish the zero of the apparatus. The table of Fig. 10 gives the results obtained during the night of 10 December 1976. The cooling source worked satisfactorily; the cooling of the mirror (down to −89.9°C, with an ambient of −68.4°C) was more than sufficient to measure a frost point of the order of −80°C. Moreover, the maximum heating of the mirror increased its temperature to −74.6°C, considerably above the expected frost-point temperature.

Except for the cooling source, the results are rather difficult to understand. The continuous increase of the mirror temperature and the heating shows that equilibrium was not reached even though the complete run of eight successive recordings took about 2 h. At the time of the first recording, the difference between the expected frost-point temperature and the maximum cooling temperature was 10°C; thus, the reaction time of the system should have been of the order of a few minutes.

5. Discussion

The behavior of the apparatus in flight was entirely different from its operation while running in the laboratory. Possible drifts of the detector or of the regulator loop for the heating would change the sensitivity of the hygrometer. The amount of frost necessary to obtain equilibrium would thus be increased, giving rise to a consequent increase in the response time of the apparatus. However, these possible drifts are rather unaccountable because, as shown earlier, a great number of laboratory tests, at very low temperatures, have been carried out.

A more credible explanation is that the growth of the frost in flight is entirely different from its growth in our laboratory experiments. Variation of shapes of ice crystals implies variation of optical properties of the deposit which can lead to a much longer response time of the hygrometer.

In addition to the influence of temperature, the size and the shape of the ice crystals growing from the vapor phase also depends on the supersaturation and on such gas physical constants as the diffusion coefficient of water vapor. Kobayashi (1965) has shown that between −50 and −90°C, ice crystals have a prismatic habit of growth either in solid prisms or in hollow sheaths depending upon the saturation ratio of the vapor.

It is apparent in Fig. 10 that the cooling rate of the mirror is rather slow because of the response time of the radiative cooling source. Indeed it takes about half an hour to obtain the lowest temperature (recording no. 4) after the maximum heating (recording no. 2). The slowly increasing voltage on the mirror heater indicates that the frost deposit was formed at very low supersaturation when the heat sink is still cooling. In the laboratory tests the cooling rate of the mirror varied much faster, with higher values of supersaturation being reached in a few minutes. At 100 mb, the diffusivity of water vapor is higher than in the laboratory experiments. Gonda and Kobayashi (1971) found that skeletal and dendritic structures develop less readily with increasing vapor diffusivity, which means that the stratospheric deposit may be more dense.

Finally, because of the complete evaporation of the deposit at the beginning of the measurement, subsequent growth may occur with substantial changes in the distribution of the nucleation sites on the mirror surface.

All these reasons may explain the difference between the apparatus behavior in flight and in the laboratory.

Further investigations concerning the deposit formation will be carried out to improve the quality of measurements in flight.

Acknowledgments. The authors are indebted to Dr. H. J. Mastenbrook for his helpful discussion and suggestions.

We thank H. Ovarlez and J. Capus who carried out the development of the instrument and the flight procedure.

Support for this research was provided by the Centre National d'Études Spatiales and by the Centre National de la Recherche Scientifique.

REFERENCES

Brewer, A. W., 1949: Evidence for a world circulation provided by measurements of helium and water vapor distribution in the stratosphere. *Quart. J. Roy. Meteor. Soc.*, **75**, 351–363.

——, 1965: The dew or frost-point hygrometer. *Humidity and Moisture*, Vol. 1, Reinhold, 135–143.

Cadet, D., 1973: Étude du gradient vertical du vent horizontal dans la stratosphère. Thèse 3e cycle, Paris.

Dobson, G. M. B., A. W. Brewer and B. M. Cwilong, 1946: Meteorology of the low stratosphere. *Proc. Roy. Soc. London*, **A185**, 144–175.

Eckert, E. R. G., 1963: *Introduction to Heat and Mass Transfer*. McGraw-Hill, 346 pp. (see pp. 115, 284–285).

Gonda, T., and M. Komabayasi, 1971: Skeletal and dendritic structures of ice crystal as a function of thermal conductivity and vapor diffusivity. *J. Meteor. Soc. Japan*, **49**, 32–41.

Harries, J. E., 1976: The distribution of water vapor in the stratosphere. *Rev. Geophys. Space Phys.*, **14**, 565–575.

Kobayashi, T., 1965: Vapor growth of ice crystals between −40 and −90°C. *J. Meteor. Soc. Japan*, **43**, 359–367.

Mastenbrook, H. J., 1968: Water distribution in the stratosphere and high troposphere. *J. Atmos. Sci.*, **25**, 299–311.

——, 1971: The variability of water vapor in the stratosphere. *J. Atmos. Sci.*, **28**, 1495–1501.

Ovarlez-Fourier, J., 1971: Etalonnage absolu et dérives au cours du temps de capteurs hygrométriques. Thèse ingénieur, Paris.

Reiter, E. R., 1971: Atmospheric transport process, Part 2: Chemical tracers. AEC Div. Tech. Inform., Oak Ridge, Tenn., 72–86.

Smith, R. M., 1968: A preview on the mass return flow of air and water vapor in the stratosphere using tritium as a tracer. *Tellus*, **20**, 76–81.

Stanford, J. L., 1973: Possible sink of stratospheric water vapor at the winter Antarctic Pole. *J. Atmos. Sci.*, **30**, 1431–1436.

Trombe, F., A Le Phat Vinh and M. Le Phat Vinh, 1964: Influence du gaz carbonique sur les abaissements de température obtenus par rayonnement du corps noir sur l'espace. *C. R. Acad. Sci.*, **258**, 5685–5688.

——, —— and ——, 1974: Description des expériences sur le refroidissement des corps terrestres. *J. Rech. C.N.R.S.*, **65**, 563–580.

Vincent, D. G., 1968: Mean meridional circulations in the Northern Hemisphere lower stratosphere during 1964 and 1965. *Quart. J. Roy. Meteor. Soc.*, **94**, 401, 333–349.

Weickmann, H. K., and C. C. Van Valin, 1972: The sources and sinks of water vapor in the upper atmosphere. *Preprints Int. Conf. Aerospace and Aeronautical Meteorology*, Washington, D.C., Amer. Meteor. Soc., 186–191.

Wylie, R. G., D. K. Davies and W. A. Caw, 1965: The basic process of the dew-point hygrometer. *Humidity and Moisture*, Vol. 1, Reinhold, 125–134.