A method to study the structure of standing lee waves and rotors

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Abstract

This account describes a method of measuring the temperature and humidity field in lee wave and rotor areas using an aircraft equipped with electrical resistance thermometers. Potential temperature lines, streamlines, can be drawn in the laminar air flow whereby areas with smooth air flow can rather effectively be distinguished from areas with turbulent air. The analysis of the actual rotor case shows that a rotor cloud and the air below form a turbulent vortex with a horizontal axis parallel to the mountain. The transition zone between smooth and turbulent air is very narrow, and turbulence appears to be most violent in this zone.

Introduction

The writer has studied for a number of years the deforming effects the Scandinavian mountain range has on the air flow crossing it; particularly the occurrence and structure of lee waves and rotors.

These observations have mainly been made over a region comprising the eastern part of the central mountain range. From the air base, where I am employed, and which is situated in this area, one has an exellent view of the mountains. I have often been able to make observations and measurements from a light aircraft and from jet planes in addition to the daily reports I have received from pilots flying in this area. The observations have chiefly consisted of:

(*a*) Frequency of occurance of wave motions and rotors (in most cases identified by their characteristic clouds) at various mountains.

(*b*) Vertical distribution of wave clouds, and their geographical position giving a measurement of the wave-length.

(*c*) Measurement of vertical motions.

(*d*) Measurement or estimation of turbulence.

(*e*) Photography and time-lapse filming.

It has been made possible to get a good picture of the relationship between the occurrence of waves and rotors and the general weather situation. With the aid of soundings and wind measurements from Frösön, it has been possible to find an empirical relation between the structure of wave motions and the wind profile and stability conditions. Some good observations have also been made by gliders in the above-mentioned mountain area. Some preliminary results were published at an earlier date [1]. At the time of this publication the number of observed cases amounts to about 500.

It is my intention to make a summary of my observations in the near future. It is clear that, with the above-mentioned methods of observation, is has not been possible to get the detail structure of the disturbed air flow, e.g. the temperature and humidity field.

A few years ago, however, a light powered aircraft was equipped with electrical resistance thermometers, British Met. Office type, Mk1 [2]. This simple device has proved very useful in detailed studies of stationary waves and rotors.

I should like to illustrate this account with an example.

Measuring method

The objective was to get a detailed picture of the distribution of temperature and humidity vertically and horizontally both in the undisturbed and disturbed air flow. This would be facilitated if the movements of the aircraft could be followed from the ground with theodolites or, still better, with the aid of radar, for it is essential to know the position of the aircraft in order to make use of measurement values.

Lacking these resources, I had to employ another method. It is absolutely necessary to have good navigation points in order to fix the position of the plane accurately. It proved best to fly at a right angle to the wind and compensate the drift in order to keep a track parallel to the mountain and to the clouds. Position-fixing would be inaccurate if flights were made at too high an altitude. With regard to vertical motions it is adviseable to fly where they are minimal, that is, between the mountain crest and the first rotor, right between the rotors, right above and right below the rotors.

But it is also possible to fly in areas with vertical motions provided they are rather uniform and the air smooth, e.g. just above the mountain crest, along the edges of wave or rotor clouds, etc. A good pilot can often manage to counter-

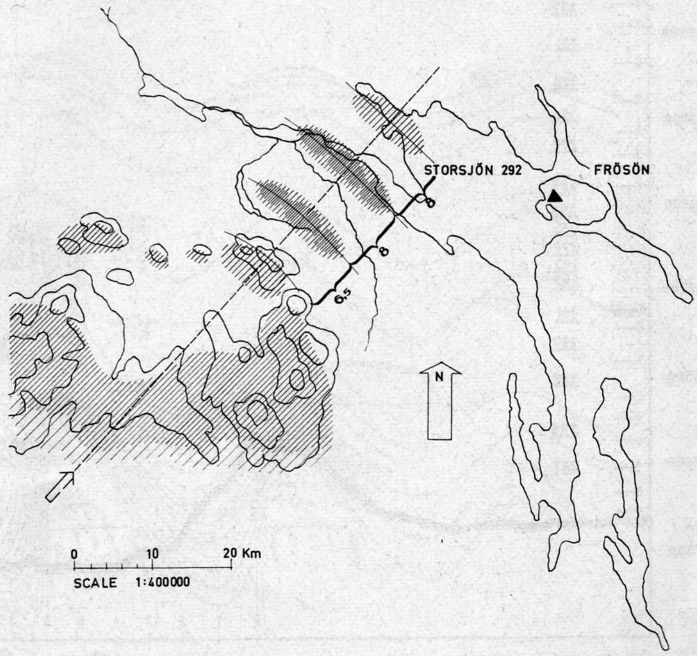

Fig. 1 Position of the three observed rotor clouds. The windward side of the mountains is covered with a thin layer of sc. The ground contours 800, 1000 and 1200 m are drawn. Black triangle (upper right) indicates airfield at Frösön

act vertical motions by varying the throttles in order to keep constant height and speed. While recording dry-and wet-bulb measurements the aircraft must keep constant height and speed. Readings should be taken along the entire length of the mountain or cloud, and can be made at least every 30 second.

While making these measurements one can get a relatively good conception of the distribution of turbulent and smooth air, and also a qualitative appreciation of the size of vertical motions and the degree of turbulence. However, flights of this type should be supplemented with flights at different levels in the direction of the wind. It is of great importance to concentrate on measuring or estimating the size and distribution of the vertical motions, and thereby eliminate temperature readings.

Observation data

Fig. 1 shows the position and extensiveness of the rotors. The flight measurements were made at 10–11 GMT. No change in the position or appearance of the rotors could be observed during this time. Flights were made in the previously mentioned manner at different levels parallel to the mountain and the rotor clouds, between, above and below the rotors. At least 3–5 dry-and wet-bulb readings were made at each level, and the aircraft kept constant height and speed at each level. The horizontal variations of temperature at a given level were rather small, not exceeding 1.5° C; the crest-line of the mountain having height differences of about 200 m. Fig. 2 shows a cross-section of the position and appearance of the rotors. On the windward side they had a hard and cumulus-like appearance whereas the surfaces of the lee sides were diffuse. The clouds tilted towards the mountain, particularly so in the case of the first rotor cloud on the top of which there lay a double pileus the whole time. The indicated values on the dry- and wet-bulb have been corrected for aircraft speed. The indicated temperatures during flight exceed the true air temperatures by an amount $\Delta T°\,F$ which is related to the true air speed v km/hr by the equation

$$\Delta T = a_D\,(v/100)^2.$$

There is some evidence that the coefficient a_D is not constant, but a function of Reynolds Number at the thermometer bulb. However, during horizontal flights which I have made on three separate occasions at eight indicated air speeds ranging from 140 to 275 km/hr, a_D was found practically constant. The deduced values of a_D were 0,40, 0,42 and 0,40. I have used a mean value of 0.41. By a similar procedure another coefficient was derived for correcting the temperatures indicated by the wet-bulb. At the usual flight speed of 220 km/hr the corrections applied to the dry-and wet-bulb readings amounted to about 2° F. It is believed that the deduced values of true air temperature and dew point are unlikely to

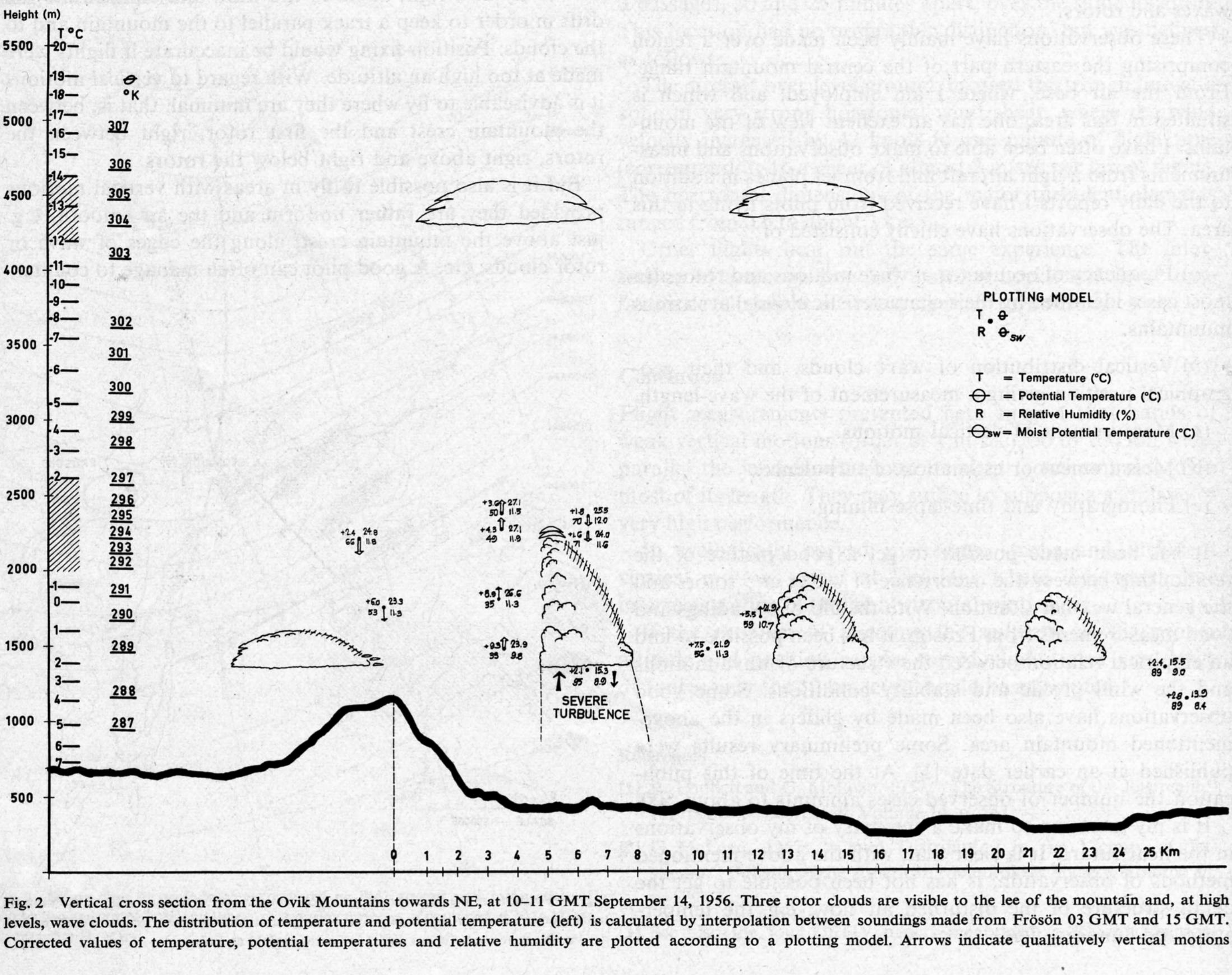

Fig. 2 Vertical cross section from the Ovik Mountains towards NE, at 10–11 GMT September 14, 1956. Three rotor clouds are visible to the lee of the mountain and, at high levels, wave clouds. The distribution of temperature and potential temperature (left) is calculated by interpolation between soundings made from Frösön 03 GMT and 15 GMT. Corrected values of temperature, potential temperatures and relative humidity are plotted according to a plotting model. Arrows indicate qualitatively vertical motions

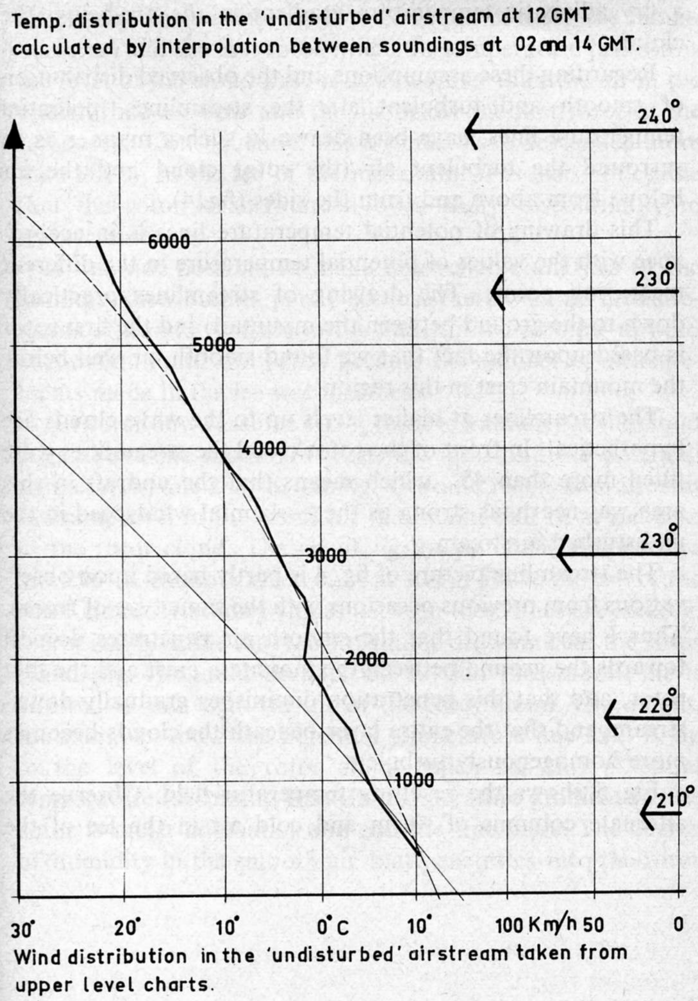

Fig. 3 Wind and temperature distribution representative of the undisturbed air flow

have errors exceeding 0.5° F and 2° F, or about 0.3° C and 1° C respectively [3]. The indicated height values have been converted to height above sea level. We have taken into account the position error of the altimeter, its calibration error and the deduced temperature field (see fig. 5). In fig. 2 corrected values of temperature, relative humidity and potential temperature have been plotted on corrected heights according to a plotting model. The arrows at the measuring points show qualitatively vertical motions—thin arrows for weak vertical motions and heavy arrows for strong vertical motions.

There was a violent turbulence below the first rotor, and measuring was not possible. However, we found a thin core just below the base of the cloud stretching along the center of the cloud in almost its entire length. We were able to make readings because the air was rather smooth here and conditions perfect for keeping constant height and speed. On the leeward side of the core there prevailed violent turbulent downdraft, and on the windside an equally turbulent updraft. It was exceedingly difficult to fly the aircraft; in the updraft we were swiftly carried into the rotor cloud, and in the turbulent downdraft the plane was forced rapidly towards the ground. Just as we entered the rotor, there was a sudden violent turbulence that ceased abruptly when leaving it, which shows that the transition zone between laminar and turbulent air was very narrow. The aircraft was not equipped with an accelerometer but the acceleration can be estimated to about ± 5 g.

No turbulence was experienced at any of the measuring points plotted in fig. 2, or in the area between the mountain crest and the first rotor where we flew a good distance below the level of the mountain crest without making any readings. In view of the risks we abandoned flying at very low height in the lee of the mountain and below the rotors.

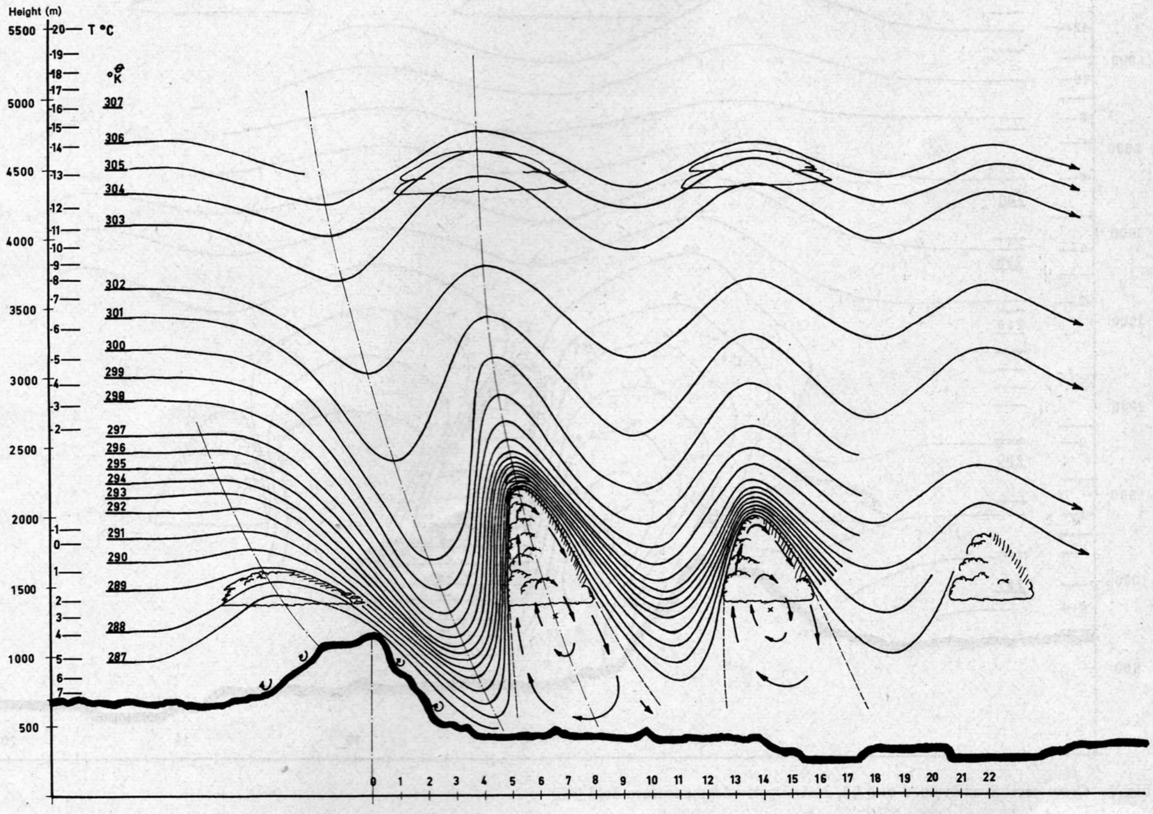

Fig. 4 Cross section as in fig. 2. Potential temperature lines are drawn on the basis of measured values and the observed distribution of smooth and turbulent air. At high levels the streamlines are hypothetical. Turbulent streaming within the rotors indicated by arrows

Further downstream from the rotors there were sc rolls at the same level as the rotors. Below these clouds the entire layer was light turbulent; above the clouds the air was smooth.

In the lee of the mountain there were stationary wave clouds at an estimated height of 4–5 thousand meters (compare fig. 2). Their positions are approximate. At high levels there were only some ci clouds, and at low levels there was a thin layer of sc clouds covering the windside of the mountains (see fig. 1).

Time did not permit an aircraft sounding on the windward side of the mountain. In order to get the temperature distribution in the undisturbed air flow I have interpolated between soundings 0300 GMT and 1500 GMT made at Frösön. The interpolated temperature curve is illustrated in fig. 3. This curve is very similar to the sounding curve 1500 GMT. The stratification is almost dry-adiabatic up to about 1000 m, there is an inversion between 2000 and 2600 m and a layer of relatively great stability between 4200 and 4600. The distribution of the temperature and the potential temperature has been plotted to the left in fig. 2.

No measurement of the upper winds was made at Frösön. The wind distribution in fig. 3 has been calculated from surface and upper level charts.

Analaysis of data

As a primary effort at analysis I have assumed that there is a moist adiabatic temperature gradient in the rotor cloud and a dry adiabatic temperature gradient in the air below the cloud.

Regarding these assumptions and the observed distribution of smooth and turbulent air, the streamlines, potential temperature lines, have been drawn in such a manner as to surround the turbulent air (the rotor cloud and the air below) from above and from the sides (fig. 4).

This drawing of potential temperature lines is in accordance with the values of potential temperature in the different measuring points. The drawing of streamlines practically down to the ground between the mountain and the first rotor is based upon the fact that we found smooth air well below the mountain crest in this region.

The streamlines at higher levels up to the wave clouds are hypothetical. In front of the rotor cloud the streamlines were tilted more than 45°, which means that the updraft in this area was nearly as strong as the horizontal windspeed in the undisturbed airstream.

The streamline picture of fig. 4 is partly based upon observations from previous occasions with the same type of rotors. Thus I have found that the smooth air penetrates deepest towards the ground between the mountain crest and the first rotor, and that this penetration diminishes gradually downstream, and that the entire layer beneath the clouds becomes more homogenously turbulent.

Fig. 5 shows the resulting temperatur field. Observe the alternate columns of warm and cold air in the lee of the

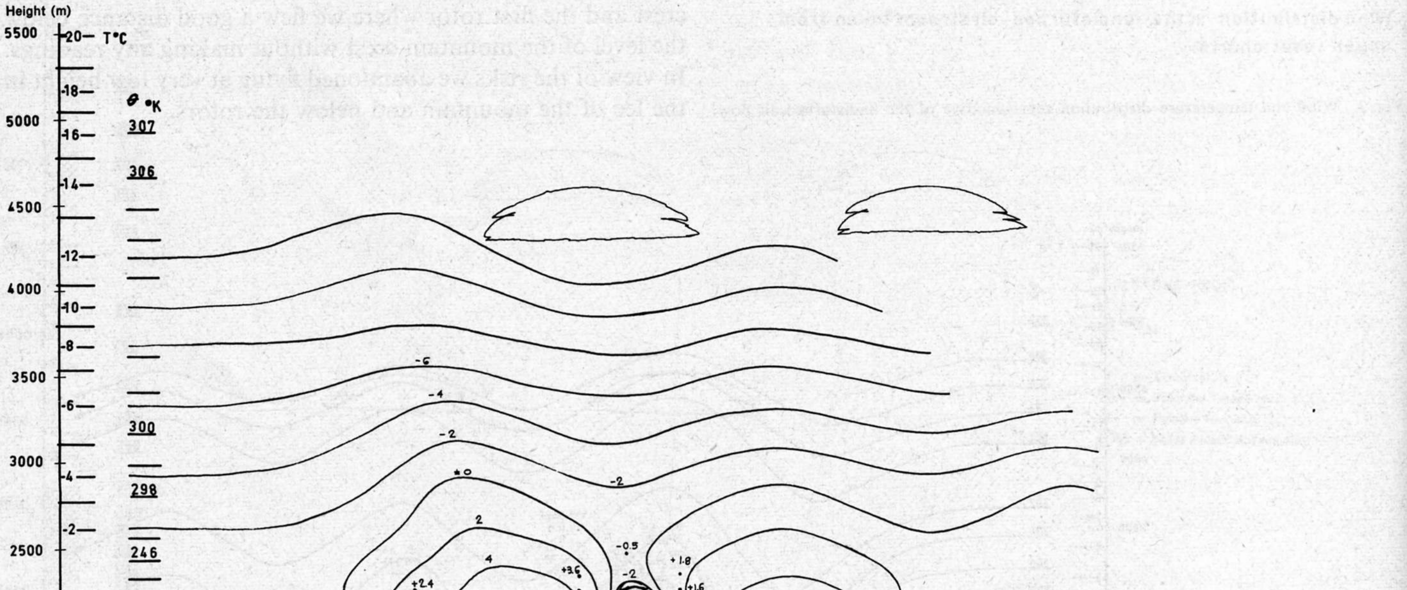

Fig 5 Cross section as in fig. 2 and fig. 3. Analysis of temperature field (°C)

mountain. The warmer air is to be found between the mountain crest and the first rotor where the temperature just below the level of the cloud base is 9° C warmer than the air in the undisturbed air flow and the air below the first rotor at the same level. Consequently, this air must have descended more than 900 m in the lee of the mountain. It is also noticeable that the rotor is surrounded by a sharp discontinuity in temperature.

It was not possible to make any reliable analysis of the humidity distribution, partly because there were no measurements of humidity made in the undisturbed air flow upwind of the mountain, and partly because the number of measurements made in the lee was insufficient.

However, if we assume 100% relative humidity at the cloud edge above the mountain crest, the air along the potential temperature line 288° K (see fig. 4) would reach saturation at the same level in the lee of the mountain, that is, at the base of the rotor cloud. The air along the potential temperature line 296° K cannot exceed 82% at 300 m above the top of the rotor cloud. Humidity values between these lines are lacking.

But it is possible that the streamline drawing near the rotor cloud (fig. 4) should be adjusted so that the smooth air is allowed to mix with the air of the rotor cloud. One might, for example, draw the potential temperature line 292° K up to the level of the rotor cloud which has this potential temperature (assuming that the temperature gradient in the rotor is moist adiabatic) and end the line there. The degree of humidity in the smooth air that penetrates into the rotor cloud will decide the amount of dilution in the cloud air. However, a dilution of the cloud air will change its temperature gradient.

Conclusion

The number of measurements was not sufficient to permit a correct analysis. However, some characteristic features in the structure of this type of rotors have been pointed out. I hope it is clear that my method can be applied with success to studies of the structure of stationary waves and rotors, especially if only moderate research funds are available.

This type of measurements should be supplemented with other types of measurements, both from the ground and in the air, as was the case in the Sierra Wave Project [4].

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