Observations of Lee Wave Clouds in the Jämtland Mountains, Sweden

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Abstract

An account is presented of three years of observations of lee-wave clouds in the Jämtland mountains, Sweden, with detailed descriptions of some individual cases. Wind and stability conditions in connection with the occurrence of the clouds are given. A brief discussion of the agreement between observed conditions and theoretical results is attempted.

1. Introduction

An air-current passing over a mountain range is subjected to various kinds of deformations as described in an account by QUENEY (1948). One of the effects often occurring even in comparatively small mountains is the development of a definite wave-pattern which usually is stationary in relation to the ground. Its existence and characteristics are determined by the vertical distribution of the wind and the temperature, the structure of the obstacle and its position relative to the wind. If the humidity is favourable – not too high – these waves may become visible through the development of lenticularis-type clouds. Under certain weather conditions the cloud-pattern over many mountain areas is characterized by such stationary wave-clouds. The air-flow over Riesengebirge and the "Moazagotl-clouds" formed there have been described in detail by KÜTTNER (1939). Other areas where wave-clouds are common can be found in Greenland, Iceland, Crossfell in England and the Italian and Swiss alps. Perhaps the most magnificent example of this phenomenon is provided by the "Sierra Wave" or the "Bishop Wave" in California (DE VER COLSON, 1952).

Glider-pilots have actively contributed to the discovery and study of these wave-upwinds and ever since their discovery in about 1930, they have utilized them for sportflight. In connection with the exploration of the wave-upwinds of the Sierra Nevada regular routine flights were made with gliders to altitudes of 10,000 – 12,000 metres.

2. Methods of observation

Observations have been conducted daily for a period of three years, October 1950 – September 1953 and were mainly concentrated to the central part of the Scandinavian mountain range shown in fig. 1. The writer has made observations partly from Frösön where a Swedish Air Force wing is stationed and from where a free view is obtained of the greater part of the area shown in fig. 1, and partly from the air in connection with daily weather reconnaisance flights over this area. In this manner and through the aid of continuous reports from specially briefed pilots it has been possible to form a satisfactory picture of when and where lee-wave clouds appear even at times when low clouds have prevented observations from the ground. In most cases it

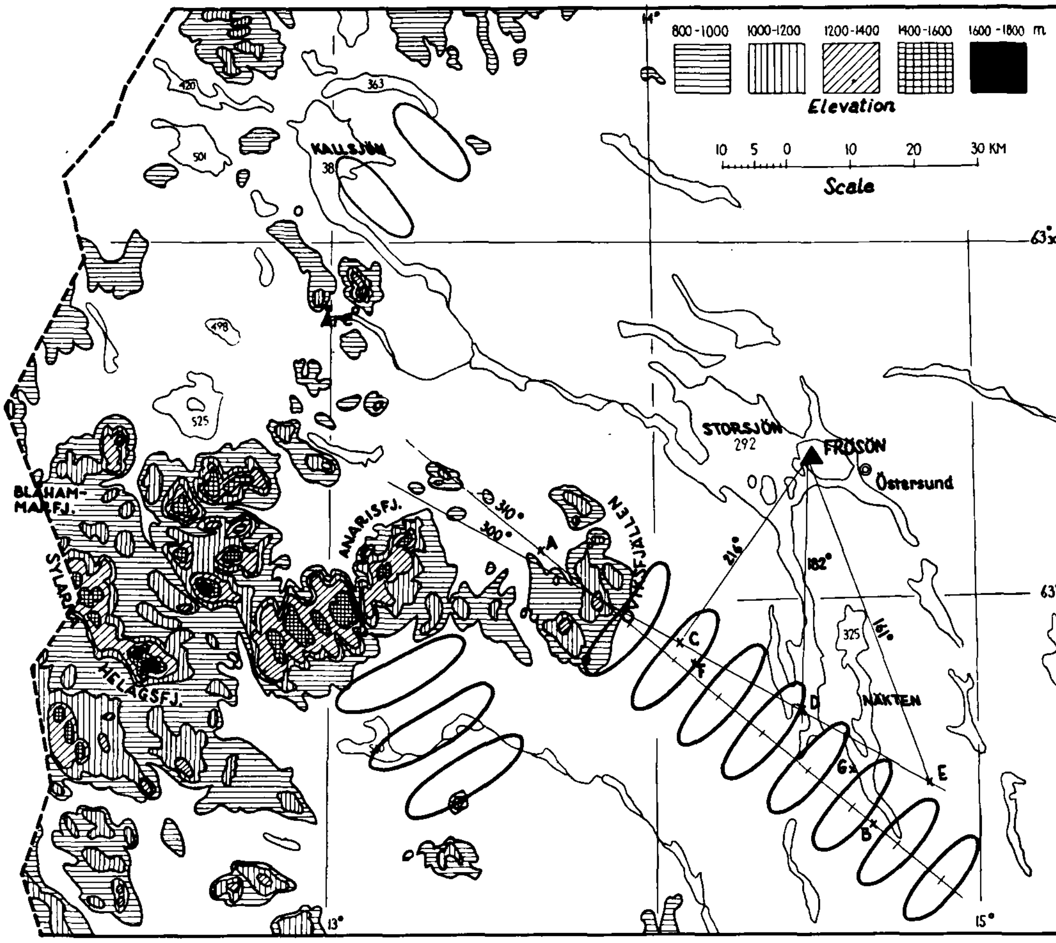

Fig. 1. Topographic map of the eastern side of the central part of the Scandinavian mountain range. The thick broken line on the left is the Norwegian Border. ▲ indicates the observation place at Frösön. The elliptical figures drawn with thick solid lines indicate the positions and the horizontal dimensions of piles of wave clouds. C, D, E, F and G also indicate positions of piles of lee wave clouds on different occasions (cf. text).

has been possible to measure or estimate the altitudes of the clouds, their size, position and persistance and to some extent structure. No instruments specially designed for these purposes were available in the air plane. Some time-lapse-filming was also undertaken. Careful notes of the observations were made. Data on wind, temperature and humidity distribution were obtained from daily radio-soundings at Frösön, 0300 and 1500 GMT. Pibals were made at 0300, 0900 and 1500 GMT or at times when wave-clouds had appeared. The wind velocity measurements at 0300 and 1500 GMT were obtained by observing the radio-sonde balloon through theodolites and the wind data thus obtained were as accurate as pibal observations by two theodolites. The wind data were determined in this manner in all cases discussed below and in most other cases.

The topographical conditions can be seen on fig. 1 which shows the eastern side of the central part of the Scandinavian mountain range. It is rather irregular but a fairly continuous mountain range extends from the mountains at the Norwegian border in the west to the Ovik Mountains in the east. The form and position of these mountains were found to be exceedingly favourable for the development of lee-wave clouds whenever WNW winds occurred. A number of lower mountains are found oriented in various directions between this range and a similar one partially shown on the northern part of the map. The Ovik Mountains, where the most beautiful trains of wave-clouds were observed, have a concave form open to the NW. The range is not entirely level but has a few peaks. The mean slope on the NW side is approximately 1 : 13 and on the SE side 1 : 8. The country is fairly level both on the NW side and SE side of the mountain and the height difference is about 700 metres.

3. Occurrence of lee-wave clouds

a. Form. The lee-wave clouds assume their most definite shape when the humidity is low, 30 – 60 %. They then resemble a lens, an almond or a cigar. Seen from the side the form is often even more like a crossection of an airfoil with the blunt side turning against the wind. The base is normally flat or concave whilst the upper side is always convex and sharply lineated. Biconvex forms have also been observed. The length of the clouds are normally the same as the obstacle, usually 10 – 30 km. The width is normally 2 – 10 km and the thickness 100 – 600 metres. With the aid of a good pair of binoculars one can see how the cloud-particles swiftly move from the windward to the leeward side of the cloud. At times the cloud disappears completely, only to be regenerated a few minutes later at the same place. In spite of strong winds it has not changed its position just above or more often to the leeward side of the mountain range. They have most commonly been observed at altitudes between 4,000 and 7,000 metres, when they appear one by one or as a few clouds behind each other. At times they are magnificently coloured in red, blue, green, and yellow. A fibrous cloud veil (snow) can sometimes be observed spreading from a stationary wave cloud far out in the direction of the wind before evaporation. Photo No. 1 provides an example. This photograph was taken on the Blåhammaren towards Sylarna at 1345 GMT on July 26, 1953. Originally the cloud was distinctly lens-shaped with an attractive irridescence. After 20 minutes a fibrous cloudveil spread out from the cloud. This continued for an hour; then the cloud disappeared entirely. The whole process was filmed with a time lapse camera which made it possible to establish that the wave-cloud remained stationary. The weather conditions were such that the pibal and the radiosounding from Frösön at 1500 GMT can be assumed to be representative for the entire observation area. Above the friction layer the wind was SSW, 10 m/sec throughout the troposphere up to 9,000 metres

Photo 1. Standing wave cloud with a veil of snow spreading out downvind.
Photograph taken from Blåhammaren towards Sylarna at 1345 GMT, July 26, 1953.

Photo 2. A train of wave clouds formed during prevailing, WNW windt on the lee side of the Anaris and Ovik Mountains. The clouds remained stationary and occured beetween 0730 and 1030 GMT. To the left there can be seen a vertical pile of wave clouds with its top at 4,200 m. The horizontal wavelength was measured to 5 km with the aid of an airplane.
Photograph taken at Frösön towards the Ovik Mountains in SW at 0815 GMT, April 17, 1953.

Photo 3. Wave clouds with cumulus below. Photograph taken ot Frösön looking west over Storsjön at 1215 GMT, May 25, 1953.

and the relative humidity was 40 – 50 %. The altitude of the cloud was estimated to be 5,000 metres corresponding to a temperature of – 10° to – 15° C. A stable layer which prevented cu-activity existed between 3,000 and 4,000 metres. Above this layer a saturated indifferent stratification was found.

When wave-clouds form "trains", the wave-movement can become clearly visible as in photos Nos 2 and 3.

The most spectacular formations of lee-wave clouds occur when wave-clouds such as those described above are located above each other in enormous piles which can extend throughout the whole troposphere (compare the situation on 5 March and 24 March). Intervals with clear sky occur between the individual wave-clouds. Piles of great vertical extension have been observed only in cases of strong winds aloft (at least 15 m/sec above the friction layer). A number of piles may occur after each other forming "trains". These have only been observed on the *leeward* side of the mountains. Most of the piles were vertical but sometimes they tilted towards or from the obstacle.

The author has observed stationary vertical piles of wave clouds extending from 2,000 m to 10,000 m consisting of up to 25 well defined cloud sheets. This happened on March 23, 1953. On that occasion they occurred in a west-north-westerly current. It is to be regretted that no photographs were taken at that time. Sometimes these clouds are identified as being cumulonimbus clouds. It is easily understood that this may happen, because of the vertical extent of the piles. Furthermore their stratified structure can not always be observed from the ground. However, the differences are very pronounced. The pile of wave clouds remains stationary and precipitation has never been observed. No significant turbulence has been observed in the clouds. Instead the upward and downward motion is very gradual but may reach values of 7 – 8 m/s. The measurements have been made with the aid of slow airplanes but never above 5,000 m. These values do probably not represent the maximum velocities occurring in such clouds. In a few cases measurements have been made in a single wave cloud or pile of wave clouds. It is then often found that the upward motion is considerably – sometimes 100 % – greater than the downward motion on the lee side of the cloud. This may indicate a strongly damped wave motion.

At the Ovik Mountains from where the majority and the most well-defined "trains" of lee-wave clouds were observed the distances (the wavelength) between the piles (wave clouds) were in many cases measured. Because of simplicity these measurements were made at lower levels. Wavelengths between 5 and 25 km, usually 8 – 10 km, were obtained. The wavelength seems mainly to depend on the wind speed, with which it increases. In some cases (e.g. 5 and 21 March) the distance from the mountain ridge to the first wave was shorter than the distances between the individual piles.

The structure of the wave clouds has not been investigated in detail. They seem, however, usually to consist of water droplets even at low temperatures. Thus some are occationally formed on the plane at – 10° C or – 15° C. In a few cases coronas have been observed in clouds at temperatures of – 25° C.

b. Frequency. Wave clouds were observed on 125 days during a period of three years, October 1950 – September 1953. Distribution per month is shown in fig. 2. In this connection only clouds, the nature of which the writer was able to classify as stationary lee-wave clouds with the equipment available, are included. Thus lenticular clouds with no obvious relation to the topography or which could not be established to be stationary have not been included.

c. The occurrence of lee-wave clouds in different weather situations. As will be seen in section d. lee-wave clouds were mainly observed during SW and NW winds, although some deviations occurred. In cases with NE-ESE winds no lee-wave clouds were seen over the area of

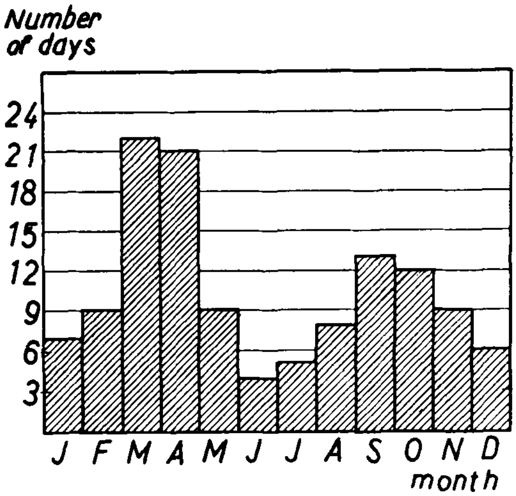

Fig. 2. The monthly distribution of 125 days whith stationary lee wave clouds, observed over the area shown in fig. 1 during the time October 1950—September 1953.

Photo 4. A pile of wave clouds formed during prevailing SW winds in a prefrontal cloud-system on the lee side of the mountains at Åre. The base of the cloud pile is about 2,000 m and the top 4,500 m.
Photograph taken from 2,800 m west of Storsjön looking northwest, at 0730 GMT, April 13, 1953.

observation, but such clouds then appeared on the Norwegian side of the range. It will also be seen from section d. that the lee-wave clouds occur in currents with practically no change in wind direction with height.

When lee-wave clouds occurred in currents, undisturbed by fronts, mainly from NW, N or SW, they were usually found at high altitudes 4,000 – 7,000 metres and nearly always in one or a few different layers. Humidity was normally low 30 – 60 %, except possibly at lower levels, where condensation often occurred on the windward side of the mountain while no clouds at all formed on the leeward side. The winds were normally strong, never below 10 m/sec above the friction layer.

Piles of wave clouds of great vertical extent on the other hand occurred practically exclusively in connection with fronts (high humidity) still mainly during NW and SW winds of great strength aloft (at least 15 – 20 m/sec above the frictionlayer). In addition high reaching piles have been observed practically only in the peripheral parts of the fronts – in pre- and post-frontal positions. The whole month of March 1953 was marked by a weather situation very favourable for the formation of lee-wave clouds. An extensive anticyclone covered Central Europe, South Scandinavia and the British Isles, while disturbances on the polar front moved on a northerly track in a very strong current from Iceland over northern Scandinavia to northwestern Russia. During 14 days lee-wave clouds appeared over the Jämtland mountains. The majority of situations to be described here occurred during this month.

When lee-wave clouds are formed ahead of an approaching front they often give the impression of moving with the front. This is not the case as was often established by the writer during flights of long duration. Actually they are first formed along mountains nearest the front and gradually new clouds are formed along mountains further away in the direction of the wind.

Photo No. 4 shows a pile of wave clouds in a prefrontal position during SW wind on 13 April 1953. According to upper level charts of 0300 GMT a practically constant SW wind prevailed over the observation area. The wind speed was 15 m/sec immediately above the friction layer and increased to 35 m/sec at 9,000 metres. The following observations were made at weather-flights by the author over the central part over the observation area 0700 – 0800 GMT: Clouds in many layers up to approximately 2,000 metres. A new layer of clouds, altostratus, at about 3,000 metres and still another at 5,500 metres. These cloud layers were continuous except in lee of the mountains where "föhn" gaps occurred. Two piles of wave clouds with an approximate position and extent shown in fig. 1, were observed to the NE of Åre. The base was at about 2,000 metres, the top at approximately 4,500 metres. Photo No. 4 shows the first pile

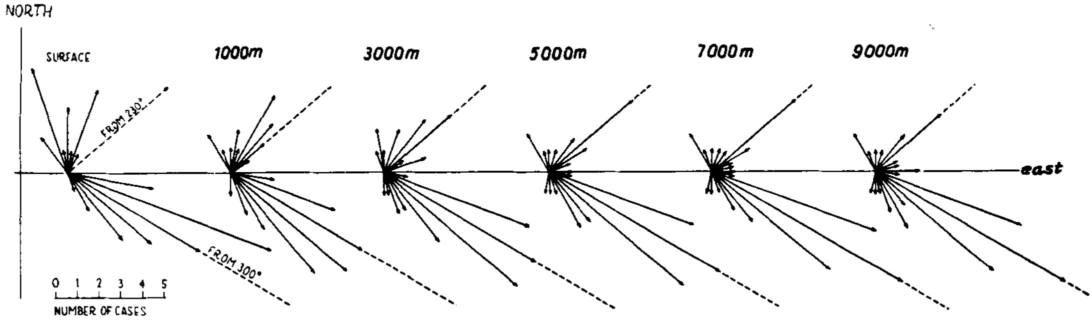

Fig. 3. Wind direction frequency for every 10 degrees at different hights. The wind data are taken from pibals made at Frösön when lee wave clouds were observed. The maximum of lee wave cloud occurence is found for WNW winds and a secondary maximum for SW winds.

as seen from the SE. Many such piles occurred on the northeastern side of the mountains further to the south.

The piles had disappeared at 1000 GMT according to reports from the pilots. The cloud layers were now without any holes and between 5,000 and 10,000 metres there was a continuous cloudcover. The radiosoundings 0300 GMT from Frösön showed strong stability in the layer close to the surface. The stratification was moist adiabatic between 1,000 and 5,500 metres. A front inversion existed between 5,500 and 6,000 metres, with approximately moist adiabatic stratification above. The humidity was high, 80 – 95 %.

d. Wind conditions. The gradient wind was calculated for the main directions S, SW, NW etc. in the 125 cases when lee-wave clouds were observed. In proportion to the frequency thus obtained, 50 cases were selected in which upper-air wind measurements were made up to 9,000 metres. (Upper-air wind measurements were not carried out in all 125 cases) A few supplementary wind data have been estimated from upper level charts. Wind direction frequency for every 10 degree calculated for the ground, 1,000, 3,000, 5,000, 7,000, and 9,000 metres are shown in fig. 3.

Maximum of lee-wave clouds occurrence is found for WNW-winds (majority of cases observed at the Ovik Mountains). A secondary maximum for SW winds (majority of cases observed on the NE side of the following mountain ranges: the Ovik Mountains – the Anaris Mountains – the Helags Mountains – the mountains at Åre). The individual cases show that the wind is from approximately the same direction at all altitudes when lee-wave clouds occur, at least up to the highest clouds (compare 5 and 21 March and 24 March). This is also suggested by fig. 3 where mainly the surface wind, due to friction, has directions deviating from those at other altitudes. The wind direction seems to be approximately at right angles to the mountains generating the wave clouds.

The average windspeed estimated from these 50 cases are indicated on fig. 4. In most cases the windspeed increased with altitude, but there are many cases in which the windspeed is constant except in the friction layer. In no cases lee-wave clouds have been observed when the wind velocity has decreased with height.

e. Stability conditions. Mean temperature curves (fig. 4) have been calculated from soundings made from Frösön during March 1953 in order to obtain an idea of the average stability conditions when lee-wave clouds occur. In these cases the soundings (altogether 19) made when wave clouds have occurred (often in all layers in the troposphere) have been compared with those (43) when wave clouds have not occurred. A considerably higher degree of stability is found in layers 1,000 – 3,000 metres and a somewhat smaller stability over 4,000 metres, than was the case when no wave clouds occurred. The values of the temperature gradient is seen in table 1.

It should be noted, however, that these conditions do not entirely represent "the undisturbed airflow". In the cases of NW winds, which were dominating, the track of the radiosonde balloon is outside the area of

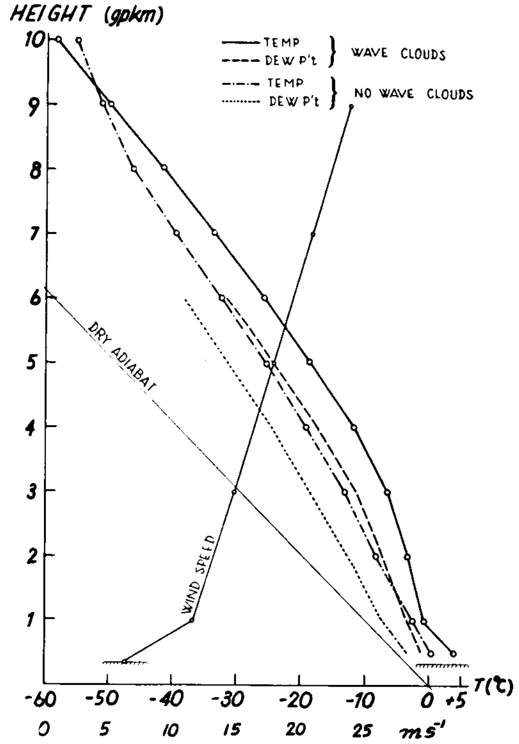

Fig. 4. Mean sounding curves for the radiosonde station at Frösön for March 1953. The soundings (altogether 19) made when wave clouds have occured, have been compared to those (43) when no wave clouds occured. The diagram also shows the mean wind speed for different levels, estimated from 50 cases with wave clouds (those in fig. 3).

the Ovik Mountains, but minor influences from mountains in NW can not be excluded. When the wind comes from SW the radiosonde balloon is even more affected by the disturbed airstream. (Compare fig. 1.)

A study of the stability conditions in the individual cases (more than 125 available, often with wave clouds through the entire troposphere) can be summarized as follows:

1. A layer of *great* stability from the ground to 2,000 – 4,000 metres and aloft low stability (nearly moist adiabatic stratification).

2. When an adiabatic layer occurs at the ground there is always an extremely stable layer above it (possibly inversion) and *low* stability aloft.

3. At times a strong inversion (front inversion) occurs aloft but it is more common that many small inversions or strongly stable layers are present between which the stratification is conditionally unstable or even absolutely unstable.

As was pointed out by Ludlam in a note to Austin (1952) the undisturbed airflow in a wavecrest can be 1 – 10° colder than in the trough at the same altitude. A radiosonde passing through a lee-wave area therefore registrates fictitious inversions with great or even superadiabatic temperature gradient between these. It has not been possible to make sure whether this is the reason for the stability conditions described in paragraph 3 above.

4. Detailed description of three cases.

Mars 5, 1953

The general weather situation was marked by an extensive anticyclone over the British Isles and Central Europe, and a depression between Jan Mayen and Spitzbergen moving ESE. Its occluded front passed the Scandinavian mountain range early in the morning and had reached western Finland at 1200 GMT, followed by a highpressure ridge west of Norway bringing NW-winds over central and northern Scandinavia. Another low at Iceland moved towards the NE with its warmfront extending from southern Norway to Iceland at 1500 GMT. The airflow in the middle and high troposphere was determined by the ridge from the British Isles over Scandinavia towards Spitzbergen. It remained practically stationary resulting in a NW high altitude flow over the observation area during the entire day.

The author made two weather flights over the area shown on fig. 1 between 0700 and 1000 GMT. At first only *sc* clouds were observed over the mountains and the inland

Table 1. Mean temperature gradient (0° C/100 m) within various layers when wave clouds occur or do not

Layer (km)	0.5—1	1—2	2—3	3—4	4—5	5—6	6—7	7—8	8—9	9—10
Lee-wave clouds	0.96	0.27	0.30	0.53	0.70	0.71	0.79	0.80	0.82	0.84
No lee-wave clouds	0.58	0.57	0.50	0.61	0.64	0.68	0.73	0.67	0.49	0.43

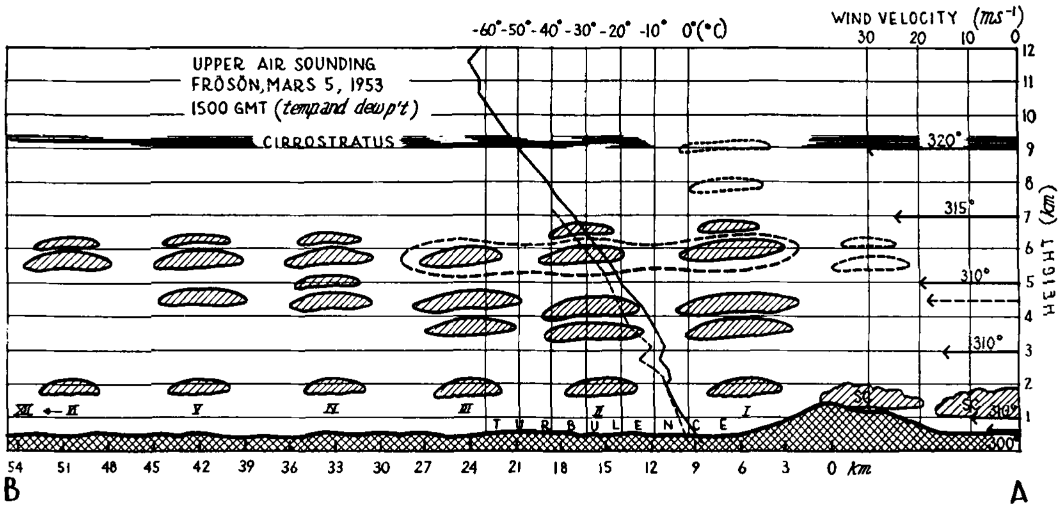

Fig. 5. Cross-section of a train of wave clouds formed on the lee side of the Ovik Mountains, March 5, 1953. The cross-section is parallel to the average wind flow aloft. Wind data computed from upper level charts are shown to the right.

but very little lee ward of the mountains. *Cs* were disappearing at the southeastern horizon. Fine wave clouds were observed over the Norwegian mountains as early as 0700 GMT at levels estimated between 3,000 and 7,000 metres. New clouds were gradually formed near the mountains further east and at 0930 GMT the first clouds were formed leewards of the Ovik Mountains (fig. 1) at many levels between 3,000 and 7,000 metres. At the same time *cs* appeared from the west. The wave clouds previously observed in the west had dissolved by this time – it should be noted that they had not been moved by the wind. Between 1000 and 1430 GMT a series of practical vertical piles were formed leeward of the Ovik Mountains (and the Anaris mountains although not measured and having a less regular structure than those at the Ovik Mountains). Each one of these piles consisted of lens-shaped clouds lying above each other and well separated from each other. The first pile tilted slightly away from the mountain. The system remained unchanged but within each pile there was a constant forming and dissolving of the individual clouds. The orientation of the system, the dimensions and position of the piles were measured from aircraft at 1000 and 1400 GMT and with the aid of a theodolite from Frösön. The distance between each pile was measured at the level where the lowest wave clouds occurred and was approximately 9 km. The individual tops of the Ovik Mountains gave rise to small irregularities both in the horizontal and the vertical direction in the system of piles, but as a whole the appearence was as shown in fig. 5. The northernmost top of the Ovik Mountains gave rise to wave clouds which were situated on the side of the main piles and had a fairly irregular character. Fig. 5 shows a schematic cross-section of the main system, as observed from the aircraft and from Frösön. The dimensions and heights of the individual clouds in the first wave were precisely measured from an aircraft at 1400 GMT. They are drawn to scale and shown in fig. 5. Other piles were not measured but the heights were estimated from the aircraft and from the ground.

Now and then a large wave cloud reaching above the piles I – III were formed at the 6,000 metres level as now and then wave clouds were formed at about the same level above the ridge and at the cirrus level (hatchered in fig. 5). The upper side of the lowest wave clouds was distinctly lens-shaped while the base was diffuse. The upper side coincided with the lower limit of the temperature inversion. 12 waves were observed at this altitude. At higher levels a smaller number of wave clouds were observed. In addition to the wave clouds *sc* and *fs*, 5 – 8/10

Photo 5. A part of a train of lee wave clouds formed on the lee side of the Ovik Mountains. The cloud pile to the right is wave I, drawn in fig. 5.
Photograph taken from Frösön towards the southwest, at 1249 GMT, March 5, 1953.

occurred at a low level, very little leeward of the mountain where the wave clouds had formed. *Sc* clouds occurred at low altitude on the windward side of the Ovik Mountains, forming a "föhn" wall on the crest. The *sc* clouds made measurement of the upper winds impossible at Frösön. The upper winds on fig. 5 are taken from upper air charts (interpolated for 0300 – 1500 GMT). Although the track of the radiosonde balloon passed 30 km north of the wave cloud area at the Ovik Mountains it is possible that the temperature sounding taken at Frösön at 1500 GMT is not entirely representative for the undisturbed current. The stratification is markedly stable (isothermal) between 2,000 and 3,000 metres, and above that moist adiabatic. Relative humidity above the inversion is 55 % – 70 %. Due to a faulty camera only one photo was acceptable. Photo No. 5 was taken from Frösön towards the waves I – III at 1240 GMT. Wave I is best developed, but in view of what has been stated above it is difficult to identify the individual clouds with those drawn in fig. 5. At 1430 GMT the system was dissolving and further observations were impossible because of the appearance of *sc* in NW.

March 21, 1953.

The weather situation is given by the 500 mb map (fig. 6) and the surface map (fig. 7) at 1500 GMT. The strong WNW flow over Central and Northern Scandinavia continued all day. At 0600 GMT the frontal system located over Finland in the afternoon was situated off the Norwegian coast with a precipitation area over the central and northern parts of the mountain range. During its passage over the mountains the front was considerably weakened by "föhn". In the mountain area orographic precipitation fell throughout the day and up to 18 mm was measured, while no precipitation at all was observed on the leeward side.

No observations from aircraft were made this day. At Frösön, *sc* and *as* had been reported since midnight and nearly 10/10 of these clouds remained at 0600 GMT. After 0700 GMT the layer of *sc* was partly broken. There were no stratified clouds, *sc*, *as* or *cs* immediately on the

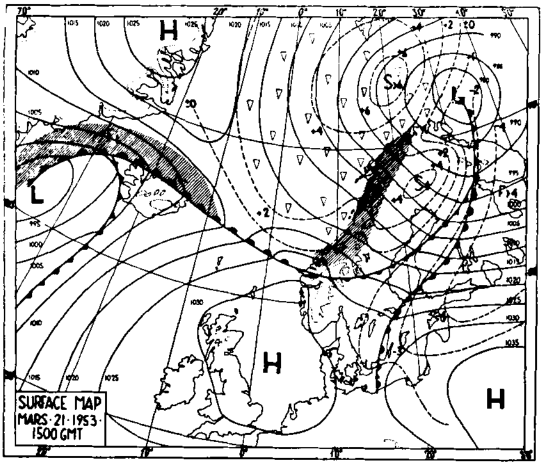

Fig. 6. 500 mb chart, March 21, 1953, 1500 GMT.

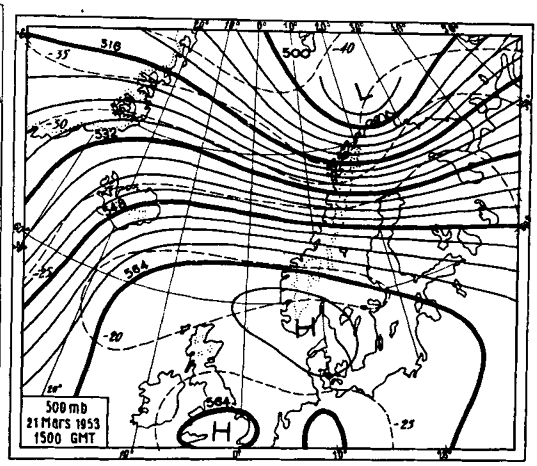

Fig. 7. Surface map, March 21, 1953, 1500 GMT.

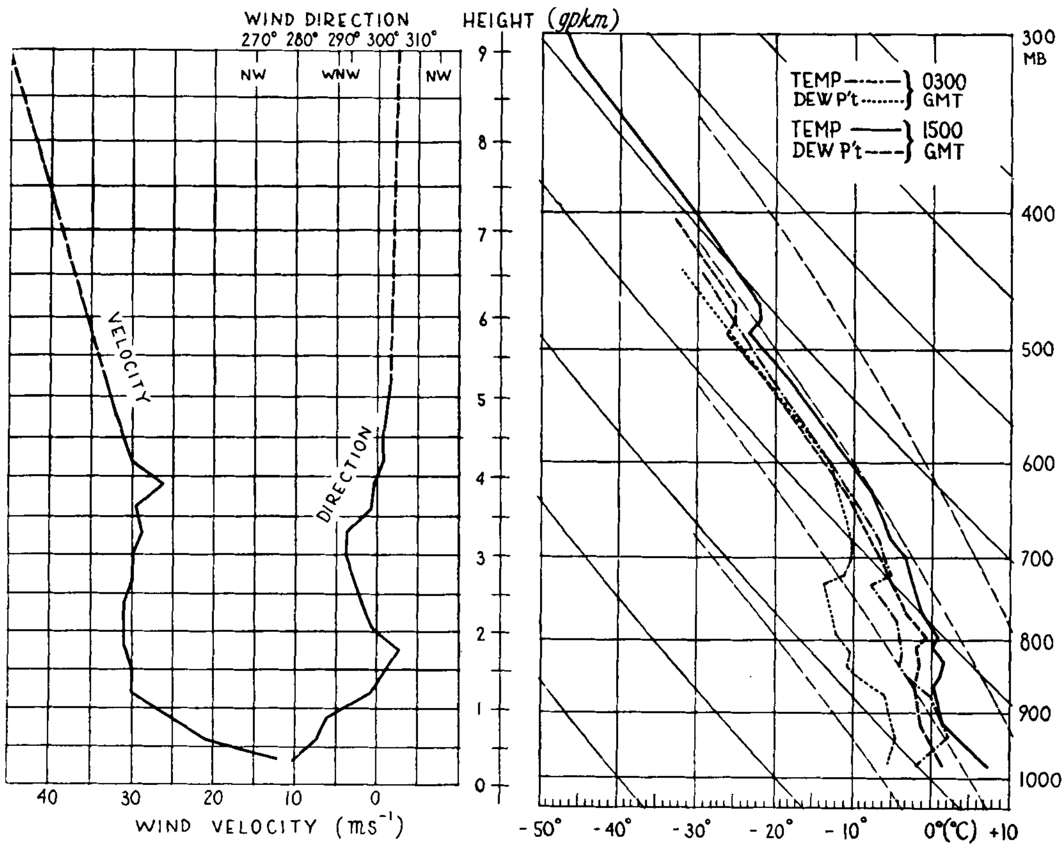

Fig. 8. Radiosonde observations from Frösön for March 21, 1953 plotted on a Väisälä Emagram. The left diagram shovs wind data from Frösön at 1500 GMT, March 21. 1953. The full thick lines represent the observed wind, and the broken thick lines represent wind data computed from upper level charts.

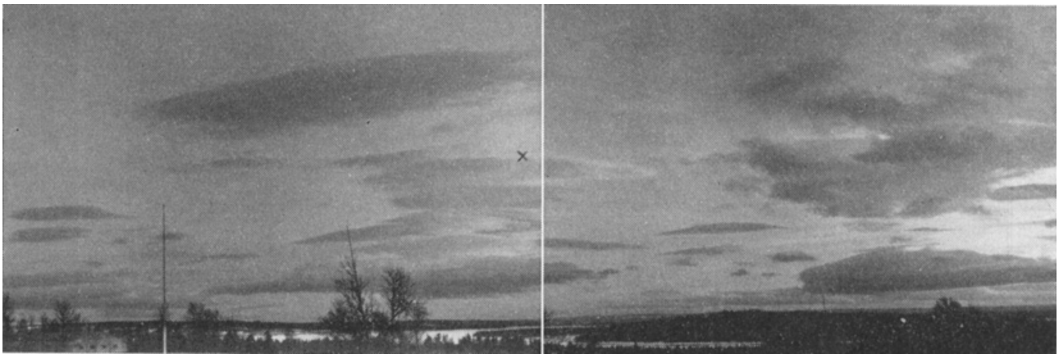

Photo 6. A panoramic view looking towards the southwest from Frösön. The Ovik Mountains are situated just outside the right edge of the picture. Three piles of wave clouds can be seen. Their positions over the ground are indicated by C, D and E in fig. 1. The top of the middle pile, marked with an »x» and tilted towards the obstacle, was about 6,000 m. The outer piles were at times as well developed as the middle one. Photograph taken at 1645 GMT, March 21, 1953.

eeward side of the mountains. Instead very high reaching piles of wave clouds had formed here. Over areas not in the immediate vicinity of mountains such as the Storsjö area the stratified clouds remained, even if somewhat broken up. The stratified clouds moved away after 0900 GMT. At that time the wind turned from SW to WNW and the temperature increased. Thus the front probably passed about 0900 GMT. Afterwards the strength of the surface wind was about 15 m/sec. and very gusty. The high piles of wave clouds remained, however, and completely dominated the sky on the leeward side of the mountains. They were particularly beautifully developed SE of the Ovik Mountains where they reached the *ci* level, probably above 10,000 metres.

Not until 1600 GMT was the writer able to take photographs and make measurements. A theodolite was used at Frösön to measure the bearing of three stationary piles of wave clouds on the leeward side of the Ovik Mountains (fig. 1). According to pibals from Frösön at 1500 GMT the wind direction was about the same, 300°, at all levels up to 5,100 metres. The winds at higher altitudes in fig. 8 have been estimated from the upper air charts at 1500 GMT. It was assumed that the wave clouds were lying directly in the direction of the wind. Thus it was possible to determine the position of the piles through the intersection of the bearings and the wind direction line, the *sc* positions being indicated as C, D and E (see fig. 1). The distance between the piles was in this way determined to 22 – 23 km. The distance from the mountain ridge to the first wave was only 14 km. On some occasions such small distances from the first wave have also been measured from aircraft (compare March 5, 1953). The top of the middle pile, marked with an "X" on photo No. 6, was estimated to reach an altitude of 6,000 metres at 1645 GMT. The wave clouds had reached the *ci* level before 1600 GMT and the outer piles were occasionally as well developed as the middle one. At this time new *cs* was being formed to the W. The base of the lower wave clouds of "rotor type" was calculated by means of a theodolite and was found to be approximately 1,000 metres. 7/10 *sc* was found at low altitude over land, particularly N and E of Frösön, but not leewards of the Ovik Mountains. *Sc* appeared also over Frösön after 1730 GMT and made further observations impossible.

When studying the temperature curve at 1500 GMT a stratification is found which is typical when wave clouds appear: a "föhn" gradient (approximately 1°/100 metres) in the lowest layer, great stability (isothermal) up to more than 2,000 metres. Above 3,000 metres the stratification is moist adiabatically unstable up to the inversion at the 6,000 metres level and also above this altitude as far up as to the tropopause at 13,200 metres. There were, however, a number of minor inversions between 9,000 metres and the tropopause (the whole temperature curve is not shown in fig. 8).

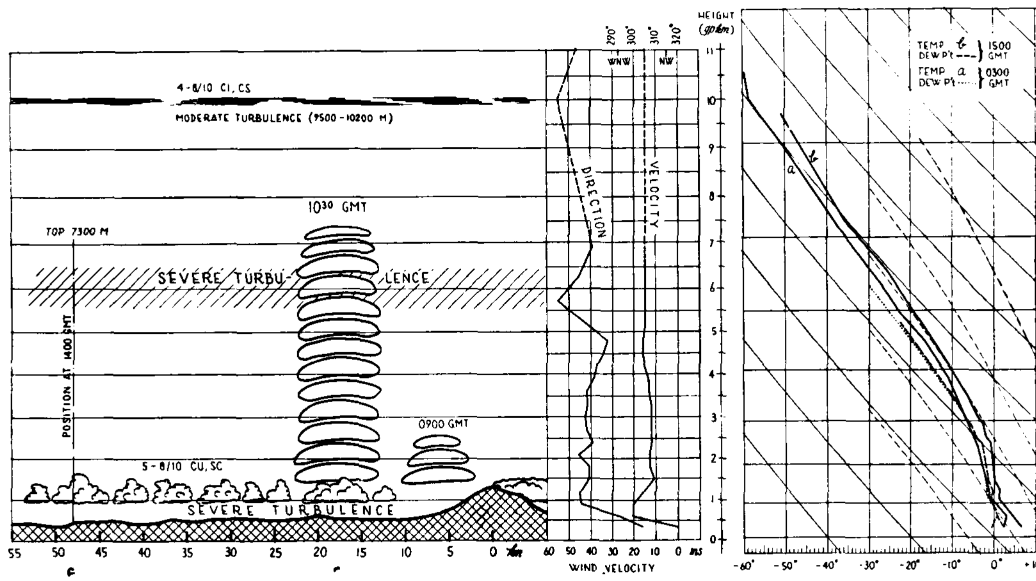

Fig. 9. The right diagram shows radiosonde observations from Frösön for March 24, 1953 plotted on a Väisälä Emagram. The middle diagram shows wind data from Frösön at 1500 GMT, March 24, 1953. Full thick lines represent observed wind and broken thick lines represent wind data computed from upper level charts. The left diagram is a schematic cross-section of wave clouds formations on the lee side of the Ovik Mountains.

March 24, 1953.

In addition to piles of wave clouds this situation permitted some other interesting observations in connection with a NW "föhn".

According to the 500 and 700 mb maps for 0300 and 1500 GMT the high pressure system remained over Central Europe and the British Isles (cf. 21 March) with a ridge over the sea between Iceland and Scandinavia. A very strong WNW wind prevailed over Scandinavia the whole day. The surface maps for March 24 showed a series of disturbances on the polar front from Iceland over Central Scandinavia to Western Russia. A small depression between Iceland and Central Norway at 0300 GMT moved swiftly ESE, immediately north of the observation area and had its centre over the Gulf of Bothnia (Kvarken) at 1500 GMT. Its warmfront passed over Frösön at about 0730 GMT. Airplane reports at 0700 GMT indicated that the cloud system consisted of stratified, fairly continuous clouds, the top of which were above 5,000 metres. After the front passage a mild strong and gusty WNW airflow penetrated into the observation area. It lasted all day and increased in strength. Following the frontal passage some clouds disappeared and the cloud cover was fairly constant over the observation area after 0800 GMT and for the rest of the day. At 10,000 metres there was 4 – 8/10 *cs* and *ci*. Turbulence strato-cumulus, 5 – 8/10, appeared at low level over land, particularly north and east of Frösön, while there were no low clouds above Storsjön or immediately on the leeward side of the Ovik Mountains. A "wall of clouds" remained stationary all day west of a line approximately through the Anaris Mountains. Its altitude was estimated to approximately 5,000 metres and it was very similar to the cloud-system of a cold front. NW of this line large quantities of precipitation fell during the day (20 – 45 millimetres). There was no precipitation in the southern and eastern parts of the observation area, apart from a few places, where precipitation totalled 1 millimetre.

After the clearing the writer observed a small pile of wave clouds at 0800 – 0930 GMT. It remained stationary leewards of the Ovik Mountains and was later dissolved. Its position and altitude was determined by means of a theodolite from Frösön (see figs. 1 and 9). The

Photo 7. Wave clouds at one level and with a short wave lenghth (about 1 km).
Photograph taken from Frösön towards the southwest, at 1200 GMT, March 24, 1953.

Photo 8. Clouds rotating around a horizontal axis and simultaneously mowing downwind. They appeared in a layer of strong wind discontinuity and turbulence (see fig. 9) at an altitude of about 6,000 m.
Photograph taken from Frösön looking towards the east, at 1255 GMT, March 24, 1953.

gradient wind at the time was WNW and approximately 15 m/sec. (Upper winds were not measured.)

Later a pilot reported (competent glider-pilot and meteorological observer) that he had determined the position and measured a *single* mighty pile of wave clouds at 1030 GMT. It was situated at F, see figs 1 and 9, that is about 18 km from the mountain crest in the wind direction. In addition to this pile and *cs*, and at low height *sc*, there were no other clouds in the vicinity. He described it as reproduced in the cross section, in fig. 1. The pile consisted of 13 wave clouds well separated from each other, with the top layer at 7,500 metres. The pile was vertical, and its horizontal extension at right angles to the wind was equal to the width of the Ovik Mountains. The pilot had been unable to observe any movement of the pile during the 30 minutes he observed it. In the afternoon the same pilot reported that the pile had "moved" and that it was situated at G at 1400 GMT, that is 48 km from the mountain crest (see figs 1 and 9). The highest wave cloud was now at 7,300 metres. The pilot described the pile as "being not quite as regular in shape as previously".

Unfortunately the writer was unable to make any observations from the air himself, and the piles were not visible at Frösön for *sc* clouds. Some other interesting observations were made, however. The wave clouds appeared at *one level* (see photo No. 7) and with a short wave length (about 1 km) leeward of the Ovik Mountains for a period of half an hour. The photo was taken from Frösön towards the SE at 1200 GMT. The altitude of the clouds was estimated at 6,000 – 7,000 metres. They appeared to be parallel to the Ovik Mountains.

Photo No. 8 shows another type of clouds which appeared chiefly over the Storsjö area, but not leewards of the Ovik Mountains in the afternoon. The photo was taken from Frösön towards the east at 1255 GMT. The clouds were in a strong rotating motion around a horizontal axis, at the same time as they moved ESE. According to reports from an aircraft they appeared at an altitude of 6,000 metres. They were thus situated in a layer of strong wind discontinuity (see fig. 9). The pilots found a layer of strong turbulence between approximately 5,500 and 6,500 metres with accelerometer readings of 6 g. There was likewise severe turbulence in the surface layer below the *sc* clouds with accelerometer readings of 7 g at speeds of 450 km/hour. As a result of their construction accelerometers do not give true readings under conditions of turbulence, but it was the general opinion of the pilots that the flying conditions were most difficult both at 6,000 metres and in the turbulent layer near the ground. Turbulence was also noticed at the tropopause level, which was described as lightmoderate within the 9,500 – 10,200 metres layer. Condensation trails from aircraft occurred within the layer at altitudes between 9,200 and 10,200 metres. The trails were *intermittent* even when the airplane maintained steady altitude and airspeed. This seems to indicate differences in horizontal humidity distribution even within very short distances.

A study of the wind distribution at 1500 GMT shows that, except in the friction layer where the wind was very gusty, the wind direction was approximately 305° throughout the troposphere. The piles of wave clouds were oriented exactly in this direction (fig. 1). Disregarding the friction layer the wind strength was practically constant up to 5,000 metres. A strong wind discontinuity existed between 5,000 and 6,000 metres. The wind velocity above 7,000 metres was estimated from the 300 and 200 mb maps at 1500 GMT. The upper air maps showed no noticable change in the direction and strength of the current at higher levels between 0300 and 1500 GMT. As already pointed out the wind intensity increased considerably at lower levels particularly in the friction layer afternoon. There is no marked difference between the 0300 and 1500 GMT stratification curves. A minor radiation inversion at 0300 GMT was dissolved during the morning. A practically adiabatic temperature gradient was found near the ground and great stability in the 1,000 – 3,000 metres layer. Above, the stratification was practically moist adiabatic up to 7,500 metres. Humidity decreased from 0300 GMT and was between 80 and 70 % above the stable layer at 1500 GMT.

Observations from the air were discontinued after 1500 GMT. There was no change in cloud conditions before nightfall.

5. Comparison between observed and theoretical results.

There are many theoretical works dealing with the deformation of an air current passing over a mountain ridge, and the formation of vertical, stationary wavesystems on the leeward side of the ridge. It is difficult to apply these theories to a real situation, however, due to the various simplified assumptions which must be made.

It may be of interest, however, to investigate whether the formula for the oscillation of an air parcel in a stable stratified atmosphere can be applied.

The time of oscillation τ is expressed

$$\tau = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{T_0}{\gamma_d - \gamma}} \tag{1}$$

where T_0 is the initial temperature, γ_d the dry adiabatic temperature gradient and γ the prevailing temperature gradient.

Here, however, we are not considering single air parcels in vertical oscillation, but an entire air layer, which is in vertical oscillation on the leeward side of the mountain ridge, which can be approximately regarded as sinusoidal oscillations. Hence, the average values, applying to the entire oscillating layer, for temperature ($\overline{T}$) and the prevailing temperature gradient (γ) should be introduced in formula (1). When we determine the wave length L we should also use the average value for the wind speed ($\overline{U}$).

Applying this to the layer where wave clouds appeared in the cases described in this article, on 5, 21 and 24 March we shall find:

March 5, 1953

$\overline{T}=245°$ K; $\gamma=0.0061°$/m and $\overline{U}=18$ m/s

that is $\tau=516$ sec. and the corresponding wave length $L=9,288$ metres (9.3 km).

The wave length actually measured was approximately 9 km.

March 21, 1953

$\overline{T}=265°$ K; $\gamma=0.0068°$/m and $\overline{U}=30$ m/s

that is $\tau=596$ sec. and $L=17,880$ metres (18 km).

The measured wave length was 22 – 23 km.

March 24, 1953

$\overline{T}=252°$ K; $\gamma=0.0060°$/m and $\overline{U}=45$ m/s

that is $\tau=517$ sec. and $L=23,265$ metres (23 km).

In this case there was only one pile of wave clouds and it is doubtful whether its distance from the mountain crest (48 km at 1400 GMT) represents the actual wave length.

In summing up it can thus be said that good correlation between the optically measured and the theoretical wave length was obtained for the case on March 5, 1953 and to some extent also for that on March 21, 1953. In some other cases the wave length has been measured and also computed from formula (1). Fairly good agreement has been obtained.

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