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MOTHER OF PEARL CLOUDS IN NORWAY

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Summary. Examination of 168 mother of pearl cloud situations in Scandinavia 1926—57 shows that mother of pearl clouds occur in the winter season, mainly in the period December—February. The clouds are generally located on the eastern side of the Norwegian mountains at 17—30 km (mean height 24 km). A close relationship is found between mother of pearl clouds and waves on the polar front. The space above the warm sector seems to be preferred, but the clouds also form relatively frequently ahead of the warm front and behind the cold front. Upper winds in the sector 260°—340° with only slight variation of direction with height seem to be necessary. In most cases the wind speed increases from the ground up to about 9 km (mean value 105 kts). Above 9 km a decrease is observed to about 50 kts at 15 km. The temperature in the stratosphere in mother of pearl cloud situations is found to be considerably lower than the average. Estimates of the dewpoints at various levels show that a temperature of ÷90° — ÷100C° is probably necessary for cloud formation. Optical measurements of the droplet size gave diameters about 2—3μ.

1. Introduction. Around the year 1870 much discussion and speculation took place in newspapers and periodicals concerning the first description in scientific literature of high iridescent clouds or, in the usual terminology, mother of pearl clouds. The absence of such basic concepts as the polar front theory, lack of observations of temperatures and winds from the upper atmosphere, incomplete surface synoptic charts, together with lack of knowledge of the basic principles of cloud physics, combined to make research into the origin and nature of these clouds a most intractable problem.

The first systematic investigation, made by Mohn [1] in 1893, showed a pronounced correlation between the formation of mother of pearl clouds and the synoptic situation. Mohn found that the clouds occurred mainly during the winter season, and usually on the downwind side of the southern Norwegian mountains and to the south of deep eastward moving depressions. Mohn's studies have since been extended by Dieterichs [2] who drew tracks of cyclones occurring at times of mother of pearl cloud observations over Southern and Northern Norway.

Størmer [3] made an important contribution to the study of mother of pearl clouds when, in 1926, by following the same procedure as in his aurora measurements, he found the height of the clouds to be 27 km. When in 1934 Størmer [4] succeeded in making further reliable height determinations, Jaumotte [5] observed a temperature of ÷75°C at the corresponding height over Belgium. By means of a series of height measurements made mainly by Størmer in conjunction with the recently improved upper air network, it has been established that the clouds usually form at heights of 20—30 km in association with low stratospheric temperatures.

At first meteorologists had difficulty in reconciling the iridescent nature of mother of pearl clouds with the temperatures at which they formed. Later, observations have shown that super-cooling of water droplets is possible to much lower temperatures than previously assumed. But, so far, super-cooling of water droplets below ÷41°C has proved unsuccessful. The nature of mother of pearl cloud elements, therefore, still provides an unsolved problem.

Mountain waves, attention to which was drawn in the years preceding the second world war, provided a possible hydrodynamic explanation of the formation of mother of pearl clouds. The similarity between these clouds and the familiar altocumulus lenticularis formed on the crests of lee waves downwind of mountain ranges, led to the assumption that mother of pearl clouds were formed similarly by mountain waves penetrating the tropopause and reaching the considerable height of 30 km. The atmospheric models which have so far been used to study the behaviour of mountain waves in the stratosphere are unrealistic, and the problem has not yet been satisfactorily solved. But there are strong indications which justify the belief that mother of pearl clouds are a mountain wave phenomenon.

For further details concerning earlier work in the study of mother of pearl clouds, reference is made to Dieterichs [2].

2. Annual variation. In an early investigation Mohn [1] collected observational data of all iridescent clouds, none of which included height determinations. How many of these were real mother of pearl clouds and how many were high altocumulus or cirrocumulus lenticularis is uncertain, as the latter at times show brilliant iridescence and may occur at any time of the year. However, as only four of Mohn's observations were in the period April—October he concluded that the occurrence of mother of pearl clouds was mainly a winter phenomenon. For the period from 1892 to 1925 there were no reports of observations of mother of pearl clouds over Scandinavia, but observations made since 1926, partly by inexperienced observers, have been collected by Størmer and used to obtain a reliable impression of the annual variation of the clouds; only observations up to 1938 have so far been published.

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Table 1. *Annual variation in observations of mother of pearl clouds.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Southern Norway 1871—92 (after Mohn) .	16	6	3	—	1	1	2	—	—	—	2	11	42
Southern Norway 1926—57 all observations (mainly after Størmer)	30	29	1	3	—	—	1	1	—	—	4	15	84
Southern Norway 1871—1957 all observations	46	35	4	3	1	1	3	1	—	—	6	26	126
Northern Scandinavia 1926—57 (after Størmer) all observations	16	15	3	—	—	—	—	—	—	—	1	7	42
Southern Norway 1926—57, "reliable" observations	20	20	1	1	—	—	—	—	—	—	1	9	52
Northern Norway 1926—57 "reliable" observations	9	3	—	—	—	—	—	—	—	—	1	4	17
Southern Norway 1946—50 all observations	4	6	1	—	—	—	1	1	—	—	—	2	15
Southern Norway 1946—50 "reliable" observations	4	6	1	—	—	—	—	—	—	—	—	2	13

Of all the observations of the clouds 86% were made in the months December, January and February (Table 1). According to Størmer's data all except two observations since 1926 were made between 13th November and 2nd April — in an interval of about 4½ months. In the first four lines of Table 1 all reports have been considered, whilst the fifth and sixth line deal with "reliable" observations. (The term "reliable" observation will be used to denote observations made by experienced meteorologists or independently by two observers.) Considering "reliable" observations only, 94% of these observations were made in the months December, January and February. The similarity between the distributions was sufficiently good to allow use to be made also of "non-reliable" observations, at least for statistical purposes. In the following sections, therefore, all observations will be used to determine, statistically, the most favourable upper wind direction, correlation between the occurrence of mother of pearl clouds and the synoptic situation etc. However, in aerological studies of specified single situations only "reliable" observations will be used.

The annual variation of mother of pearl clouds has often been associated with the occurrence of deep winter cyclones. However, deep cyclones occur during late autumn, winter and early spring, i.e. a longer period than might have been expected from consideration of Table 1. It has also been observed that only a few intense winter cyclones result in the formation of the clouds. It is necessary, therefore, to consider other factors which might be of importance in giving suitable conditions for mother of pearl cloud formation; two such factors which come immediately to mind are the winds and temperatures in the stratosphere. As the clouds have been observed to form usually in a WNW wind, a study has been made of the annual variation of winds (Table 2) and temperatures (Table 3) for Lerwick, a radiosonde station situated about 500 km WNW of the area in which the clouds have usually occurred [6]. (A similar study for Northern Scandinavia cannot be made as relevant upper air observations have not been made with sufficient regularity.)

As will be shown later, an upper wind from about 300° is most frequent in mother of pearl cloud situations, and 78% of the observations (and 87% of the "reliable" ones) had upper winds between 260° and 340°. Comparison between Tables 1 and 2 show

Table 2. *Annual variation of the frequency (%) of stratospheric winds stronger than 30 knots and from directions 260°—340° (Lerwick 1946—50).*

		Jan	Feb	Mar	Apr	May/Aug	Sep	Oct	Nov	Dec
100 mb	30—39 knots	9,6	15,7	16,5	7,3	—	9,6	10,2	18,1	19,4
	40—49 knots	12,4	30,0	28,3	6,7	—	1,0	4,9	7,5	19,4
	>50 knots	11,1	9,4	11,8	1,1	—	0,6	—	—	0,4
60 mb	>30 knots	5,6	68,4	35,3	4,0	—	—	18,6	27,0	42,1

good agreement, with pronounced maximum frequencies in winter and zero in summer, but contains some disagreement in the month of change from high to low frequency and vice-versa. March, for example, gives a higher frequency of "favourable" winds than Table 1 would indicate. The number of 100 mb wind observations is sufficient to obtain a reliable impression of frequency of winds at 15,5 km, whilst the scarcity of 60 mb wind observations only gives a superficial impression of frequency of winds at 19 km. 15,5 km is far below the height at which mother of pearl clouds usually form and at this level the wind field is still determined partly by the tropospheric synoptic situation. Above 20 km, on the other hand, the wind field is controlled by the deep polar winter low pressure area and the polar summer anticyclone. These systems give, in northern latitudes, strong W-ly winds, increasing with height from 20 to 60 km in winter and changing from W-ly to light E-ly above 20—30 km in summer. The mean winds and temperature conditions have recently been reviewed by Murgatroyd [7]. It has been shown, by Foldvik and Palm [8], that the usual winter wind profile with W-ly winds at all levels, increasing from the surface to 10 km, decreasing from 10 to 15 km and increasing again up to 60 km is highly favourable for the formation of mountain waves with long wavelengths. Although summer situations, with almost calm conditions from 15 to 50 km have not yet been satisfactorily studied by theoretical methods, it is believed that waves in such conditions would be of small wavelength and small amplitude. Humidity measurements from the lower stratosphere indicate that great amplitudes are necessary for mother of pearl cloud formation, and it must be assumed that favourable conditions are only likely to occur in the winter season.

It has been found, as will be shown later, that a good correlation exists between the occurrence of mother of pearl clouds and low stratospheric temperatures. Table 3 shows, for Lerwick, frequency of temperatures below ÷88°F (÷66,7°C) at 100 mb and below ÷92 (÷68,9°C) at 60 mb. These values have been chosen in accordance with the mean values found in section 11. Table 3 has the same general features as Table 2, but is in better agreement with Table 1 for the months September—October.

Table 3. *Annual variation of the frequency* (%) *of temperatures below ÷88°F at 100 mb and ÷92°F at 60 mb (Lerwick 1946—50).*

	Jan	Feb	Mar	Apr	May—Oct	Nov	Dec
100 mb	3,1	8,9	11,2	0,3	—	1,4	4,3
60 mb	12,8	18,1	10,6	—	—	6,9	6,6

To summarise, it has been noted that the annual variation of certain stratospheric parameters (wind and temperature) is in good accordance with the annual variation of mother of pearl clouds. With regard to the fact that complete agreement has not been found it must be remembered that the upper air data used were for Lerwick, some 500 km from the area in which the clouds generally occur. It is possible that a similar study for the Norwegian radiosonde stations Sola or Gardermoen would have given more convincing results. Furthermore, it must also be remembered that observations of mother of pearl clouds are dependent on such factors as amount of tropospheric clouds as well as time of day. Instances of mother of pearl clouds occurring at night have only rarely been observed.

3. Determination of height. As mentioned in the introduction, the first reliable height determination of mother of pearl clouds was made by Størmer [3] in 1926. Since then a series of similar determinations has been made, also by Størmer, [4, 9, 10], together with other measurements of a somewhat more casual character. The latter, however, agree very well with Størmer's results and have been regarded as being representative. Table 4 shows all the available data. The mean value of the 16 observations is 24 km and, except for that of 5th January 1957, all heights were in the interval 17,2—30,6 km. The lower limit of mother of pearl clouds is only a matter of definition. It is hardly possible to distinguish between high, wavy, and iridescent cirrus — and what are known as mother of pearl clouds. On the other hand, as will be shown later, mother of pearl clouds are unlikely to form above 31 km.

Table 4. *Measurements of height of mother of pearl clouds.*

Date	Height (in km)		Wavy Cirrus	Way of observing
	Mean	Range		
30/12 1926	27,7	26,1—29,3		Photogrammetric
13/ 1 1929	24,1	22,5—25,5		Photogrammetric
12/ 2 1930	24,0	22,4—25,6	12,5 ±1,5	Photogrammetric
29/ 1 1932	27,4	25,6—29,0		Photogrammetric
1/ 2 1932	about 23			Combined drawing and photo
19/ 2 1932 evening	24,8	22,5—27,4		Photogrammetric
19—20/2 1932 night	23,2	21,5—24,9		Photogrammetric
6/ 2 1934	24,7	22,8—27,1	12,1 ±1,2	Photogrammetric
22/ 1 1935	probably 18			Visual observations
30/ 1 1944	28,0	23,8—29,9		Photogrammetric
5/ 1 1946	27,3	22,8—30,6		Photogrammetric
16/ 2 1946	21,0	17,2—23,6		Photogrammetric
4/ 2 1949	24,5	22,3—28,7		Photogrammetric
29/ 2 1956	21,5	20,1—23,6		Photogrammetric (Observations with theodolite gave slightly lower values)
5/ 1 1957	about 15			Time of sunset at the cloud level
9/ 1 1957	24,1	21,6—27(?)		Triangulation Blindern—Gardermoen

In Table 4 the heights of such wavy cirrus, in situations when mother of pearl clouds formed, are given. The cirrus clouds on these occasions were probably situated near the tropopause of the tropical air, in relatively humid air.

4. Determinations of wavelength. The wavelength of high lenticular clouds was measured by Størmer [4] in 1934 on an occasion in which he found, on his photographs, some cirrus of a pronounced wavy character. The height was, as mentioned in Table 4, 12,1 km, amplitude 750 m and wavelength 40 km. Up to that time the existence of such long waves was unknown, but later observations have shown that they occur relatively frequently at high altitudes. Georgii [11] mentions 40 km as a normal wavelength at 10 km and Gotaas [12] has found wavelengths of 30—40 km at 7,5 km over Southern Norway.

Apart from a preliminary report [13], the author is unaware of any published measurements of the wavelength at 20—30 km. Determinations of mother of pearl cloud wavelength, similar to those for cirrus made by Størmer, were not possible with the available observational data. Stratospheric relative humidities are such that the clouds would only form near the crests of waves and, even if they became partly or wholly ice, the individual cloud particles would evaporate before reaching the next wave trough. If, therefore, two clouds formed on consecutive crests of the same wave train they would appear as distinct clouds not linked in any way. Observational accuracy is such that it would not be possible to determine whether the line joining two distinct clouds was, in fact, parallel to the wind direction, and, even if this were possible, doubt would still exist as to whether these clouds had, or had not, formed on consecutive crests. But, if it is accepted that the distance between two clouds, having an orientation, as well as can be determined, parallel to the wind direction, would represent the wavelength, then values have been found which differ surprisingly little from each other. Furthermore, good agreement has been found with values at lower levels. The results of such measurements from 10 situations are shown in Table 5. The mean value was found to be 39,5 km and, apart from one case, all values were within $\pm$ 5,5 km of the mean.

Table 5. *Wavelength of mother of pearl clouds.*

	Date	Wave-length (km)	Height (km)	Height of Ci (km)
1	30/12 1926	35	27,7 ±1,6	
2	13/ 1 1929	42	24,1 ±1,6	
3	12/ 2 1930	37	24,0 ±1,6	12,6 ±1,5
4	29/ 1 1932	45	27,4 ±1,8	
5	19/ 2 1932	42	24,8 ±2,6	
6	20/ 2 1932	30	23,2 ±1,7	
7a	6/ 2 1934	45	24,7 ±2,4	12,1 ±1,2
7b	6/ 2 1934	40	24,7 ±2,4	
8	16/ 2 1946	40	21,0 ±3,8	
9	29/ 2 1956	39	21,5 ±2,1	
Mean		39,5	24,3	12.4

Foldvik and Palm [8] have recently made theoretical estimates of wavelengths, at high levels, of mountain waves. For the purpose of these estimates wind and temperature profiles were constructed which agreed very well, up to 20 km, with observations made in mother of pearl cloud situations. Above 20 km, as a first approximation, it was assumed that $SU^{-2} \langle\langle k^2$, k being the wave number and S the stability factor $(\gamma_a - \gamma)gT^{-1}$ (γ_a is the dry adiabatic lapse rate, γ the observed lapse rate, g the acceleration due to gravity, T the absolute temperature, whilst U is the wind speed). Work is now being undertaken, by the same writers, in which the conditions above 20 km will be reproduced as realistically as possible. Two numerical calculations with the simplified model gave wavelengths of 24,1 and 39,4 km, the latter being in good agreement with the observed mean value.

With the reservations already mentioned, Table 5 shows that 40 km is a wavelength which often occurs in mother of pearl cloud situations. It is not, however, justified to conclude that 40 km is a typical wavelength. Sometimes the clouds have had a mackerel appearance with, apparently, very short wavelenghts and on many occasions it has proved impossible to define a wavelength of the order mentioned above.

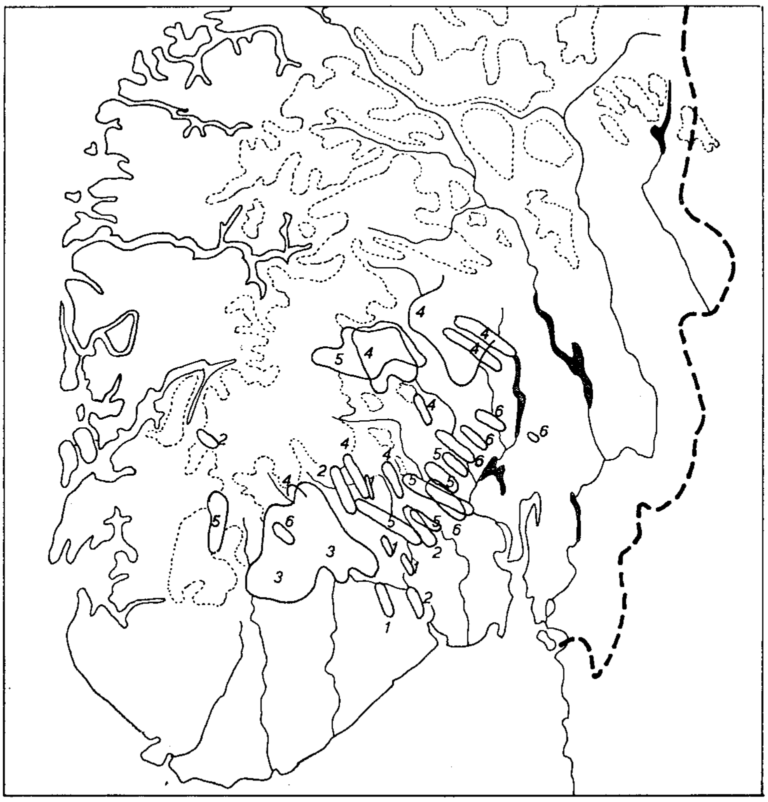

Fig. 1a: Geographical distribution of mother of pearl clouds (1: 30th December 1926, 2: 13th January 1929, 3: 12th February 1930, 4: 29th January 1932, 5: 19th February 1932, 6: 19—20th February 1932.)

5. Geographical distribution of mother of pearl clouds. Mother of pearl clouds have been seen from almost all parts of Norway, but by far the greatest number of reports come from Eastern Norway. However, in mother of pearl cloud situations, with upper winds from W to N, the lower, tropospheric clouds would tend to dissipate on the lee side of the Norwegian massif. Eastern Norway would thus be free of low clouds whilst Western Norway and Trøndelag would be covered. Similarly, in Nordland, on the western side of the mountain range, the clouds have rarely been seen, but in Troms and Finnmark they have been seen relatively often, although for only short periods and often through breaks in the lower clouds. The clouds have generally been observed about sunrise (to the E—SE) and sunset (to the SW—W), the iridiscence being most marked with the sun below the horizon. As the angular distance between the iridescent cloud and the sun would be less than 40° [1] and in the mean about 20°, it follows that the clouds would usually be situated some considerable distance from the observer, (about 150 km generally). Hence a chart showing geographical distribution of observations without mention of elevation and azimuth would possibly be misleading.

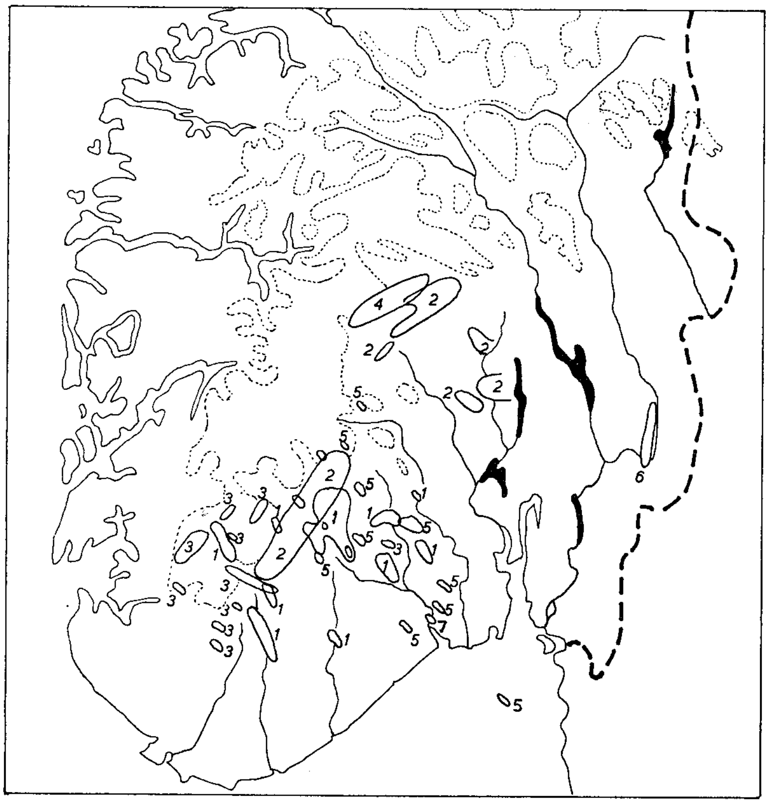

Fig. 1b: Geographical distribution of mother of pearl clouds.
(1: 6th February 1932, 2: 30th January 1944, 3: 16th February 1946,
4: 4th February 1949, 5: 29th February 1956, 6: 5th January 1946,
7: 9th January 1957.)

A series of calculations of positions of mother of pearl clouds has been made by Størmer. Similar calculations, using other, less reliable observations, have been made by the author. All the available results have been reproduced in Figures 1a and 1b. Although these observations were made almost entirely about sunset near Oslo it is the author's opinion that the distribution shown was not influenced too much by the restricted selection of situations. For instance it has often been observed that, in situations similar to those in which mother of pearl clouds form, the same regions form a preferred area for wavy cirrus. If we accept the view that mother of pearl clouds are formed in connection with mountain waves, the mountains responsible for the clouds whose positions are shown in Figure 1 were those south of Hardangervidda (tops up to 1700 m), Gausta (1883 m), the mountains in Jotunheimen (tops up to 2469 m), Snøhetta (2286 m) and Rondane (2183 m).

Visual observations have indicated that mother of pearl clouds occasionally occur over central parts of Sweden. For instance on 1st February 1932 an extensive cloud [9] was situated about 70—250 km WNW of Stockholm, and the cloud seen from Gardermoen 29th November 1953, assuming a height of 25 km, have been situated over Lake Vänern.

Although it has not been possible to compute exactly the positions of mother of pearl clouds in other parts of Scandinavia, the observations indicate that Troms, Finnmark, Northern Sweden and North-Western Finland are preferred regions.

Visual observations, as well as photographic and theodolite measurements, show that mother of pearl clouds in general are stationary clouds, in agreement with the usual assumption in theoretical treatment of the mountain wave problem. On some occasions, however, both visual observations and photographic measurements have shown movement of the clouds. Størmer has measured the movement of non-stationary clouds on five occasions (Table 6). On four of these the velocities were of the same order of magnitude as the wind speed generally observed in mother of pearl cloud situations at the relevant height. On the fifth occasion, 30th December 1926, a value (72 m/s) of about five times the usual wind speed was observed. In this connection it might be of interest to mention that, on another occasion, 18th February 1946, when mother of pearl clouds occurred, the unusual high wind speed of 73 m/s was observed at 23,5 km over Lerwick. This shows that the high velocity of mother of pearl clouds found by Størmer was not necessarily greater than the wind speed.

Table 6. *Velocity of non-stationary mother of pearl clouds (according to Størmer's observations).*

Date	Velocity (m/s)
30/12 1926	72
29/ 1 1932	10—12
19/ 2 1932	11—13
20/ 2 1932	8—9
4/ 2 1934	10—18

The movement of mother of pearl clouds has often been discussed and doubt has been thrown as to the reliability of the observations. In theoretical considerations the parameters (temperature and wind profiles) have always been regarded as constants, leading to fixed values of the wavelength. Fluctuations in the parameters governing the wavelength can explain small displacements of the wave clouds, but velocities of the order of magnitude given in Table 6 can only be explained as a sudden break-down of the wave motion. In such cases it is possible that the clouds would blow away with the same speed as the wind, becoming gradually more diffuse.

The solution of this problem looks very difficult, and better and more frequent wind observations combined with good photographic determinations of the movements of the clouds would seem to be necessary before any progress can be made.

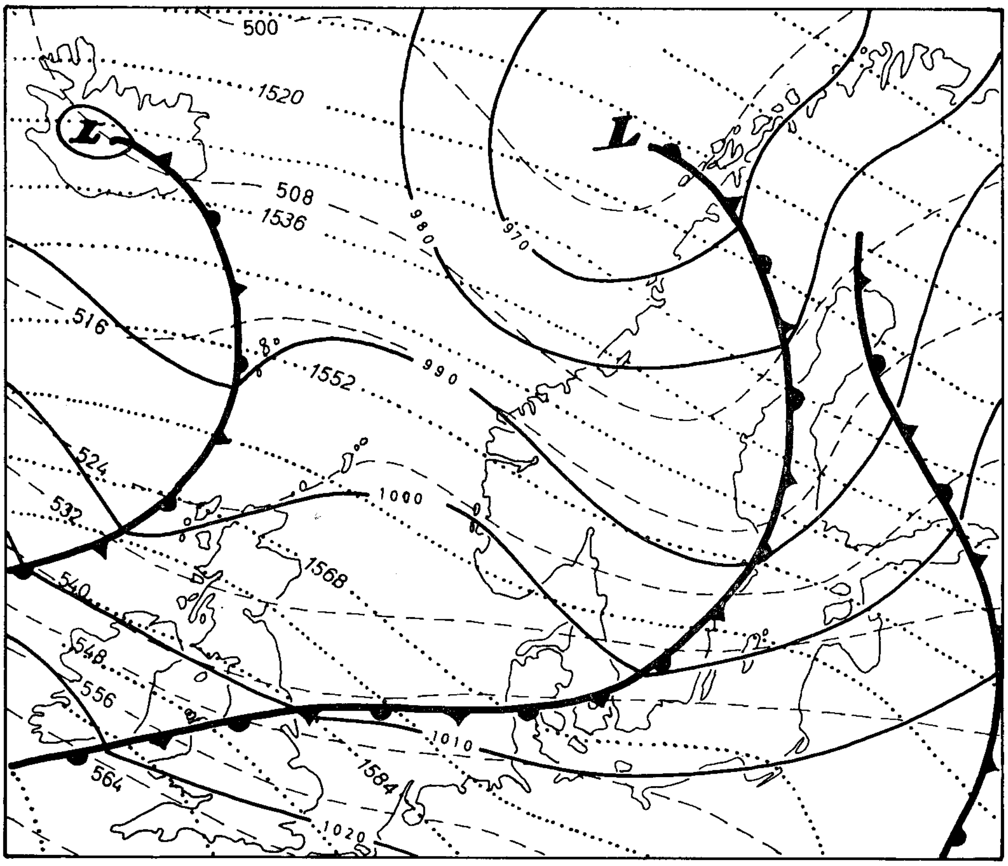

Fig. 2: Synoptic weather charts for 29th February 1956. Solid lines: surface chart 1200 GMT, broken lines: 500 mb contours 1500 GMT, dotted lines: 100 mb contours 0300 GMT. See also Figure 9.

6. Connection between the synoptic situation and the formation of mother of pearl clouds. Mohn [1] and Dieterichs [2], both of whom studied the surface synoptic situations on occasions of mother of pearl clouds, found that the clouds usually occurred to the south of deep, eastward moving depressions. After the development of the polar front theory, and its acceptance in meteorological literature, it was generally thought that mother of pearl clouds formed after the passage of the cold front. An analysis of the distribution of mother pearl clouds with respect to polar front waves (Table 7) has shown, however, that this is not correct. The classification used in Table 7 was somewhat subjective; for instance, "far behind a cold front" could also mean "far ahead of a warm front", reference being made to a subsequent frontal wave. Also, in some situations, the clouds persisted for a long time with changing surface synoptic situation; these cases were, in Table 7, counted twice, thus explaining the discrepancy in number of cases between Tables 1 and 7.

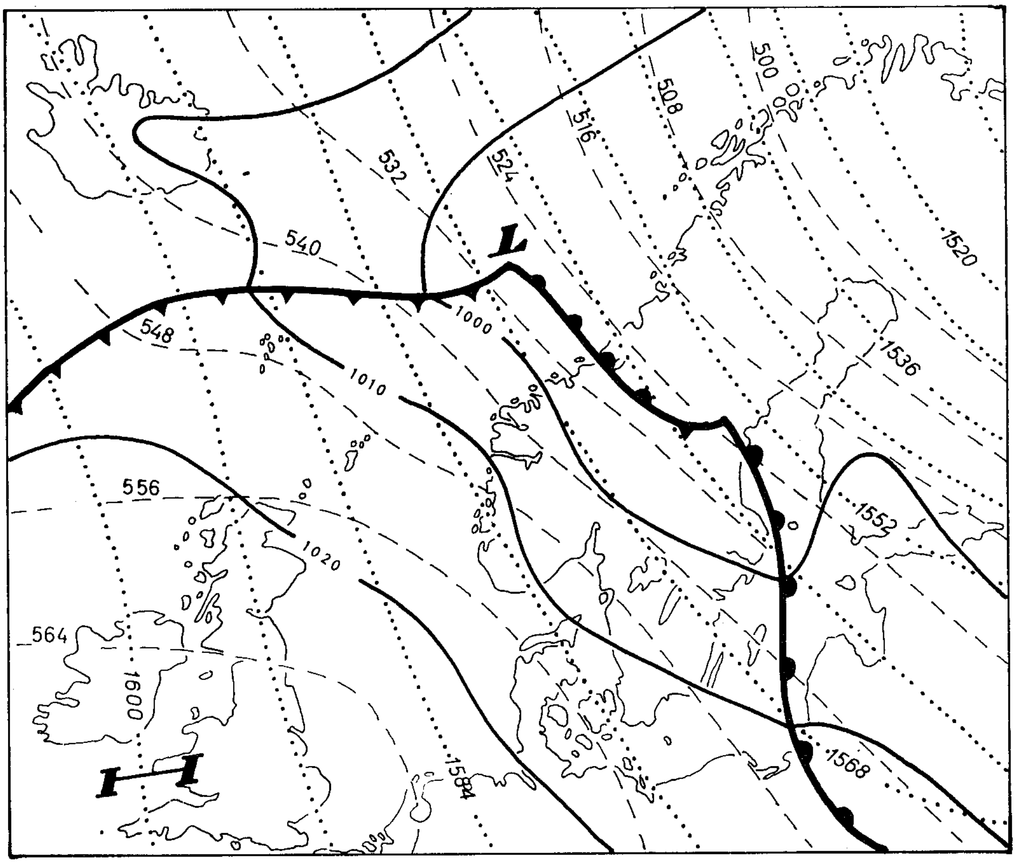

Fig. 3: Synoptic weather charts for 2nd April 1956. Solid lines: surface chart 1200 GMT, broken lines: 500 mb contours 1500 GMT, dotted lines: 100 mb contours 0300 GMT. See also Figure 10.

Out of 90 mother of pearl cloud observations in Southern Norway only 6, none of them being "reliable", showed no connection with a frontal wave. Among these 6 were the two summer situations, noted in line 2 of Table 1, which did not fulfil the wind and temperature criteria found in the next sections. This strengthened the belief that mother of pearl clouds are a winter phenomenon. As none of the remaining four situations fulfilled the wind criterion mentioned above, it was assumed that some connection existed between mother of pearl clouds and polar front waves. Simplifying Table 7, the following distribution of mother of pearl clouds was found (for Southern Norway):

Far ahead of warm front or occlusion .	4,4%	(3,5%)
Just ahead of warm front or occlusion .	16,7%	(13,8%)
In the warm sector	31,3%	(34,5%)

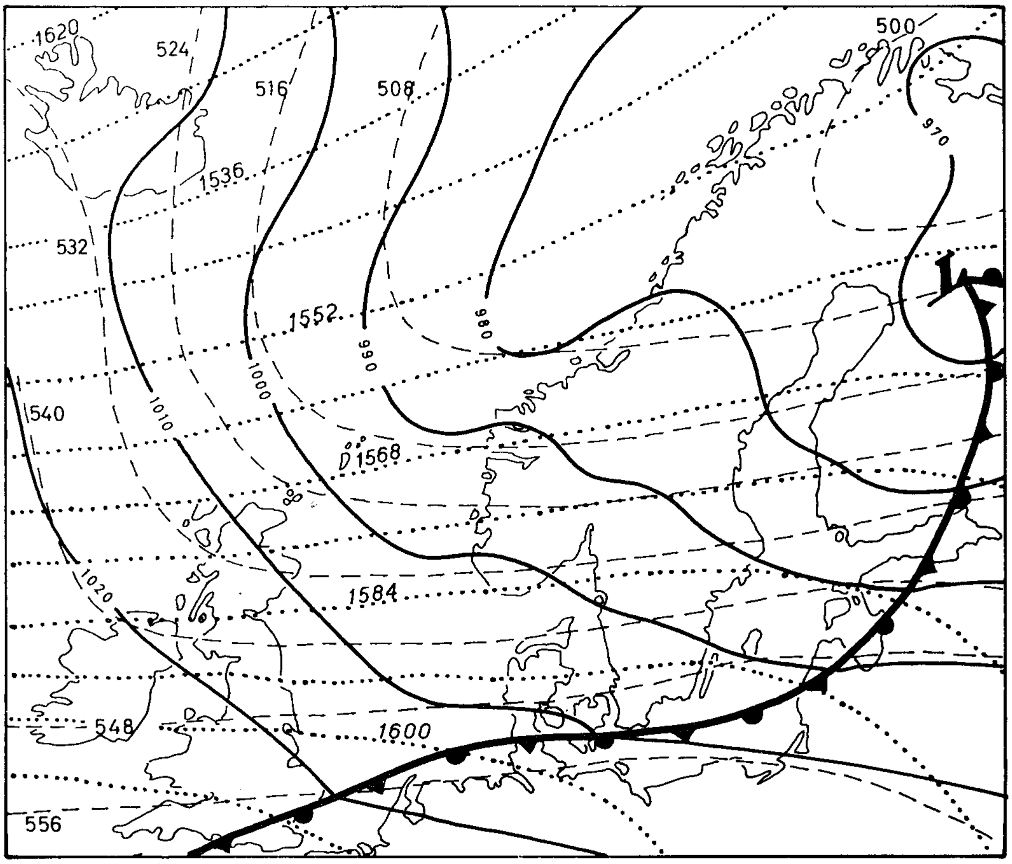

Fig. 4: Synoptic weather charts for 9th January 1957. Solid lines: surface chart 1500 GMT, broken lines: 500 mb contours 1500 GMT, dotted lines: 100 mb contours 0300 GMT. See also Figure 11.

Just behind cold front or occlusion ...	26,7%	(32,7%)
Far behind cold front or occlusion ...	14,4%	(15,5%)
Not classified	6,7%	(0%)

The numbers in brackets refer to "reliable" observations only.

The observations from Northern Scandinavia showed a distribution which was only slightly different. Hence mother of pearl clouds seem to form preferentially near the centre line of the wave ("centre line" being used to denote a line midway between the warm and cold fronts of a wave), with conditions becoming less "favourable" away from the centre line. There did, however, appear to be some bias towards the area behind the cold front, and even far behind the wave, mother of pearl clouds have been observed relatively frequently. This scewness may be only apparent: with the SW-ly

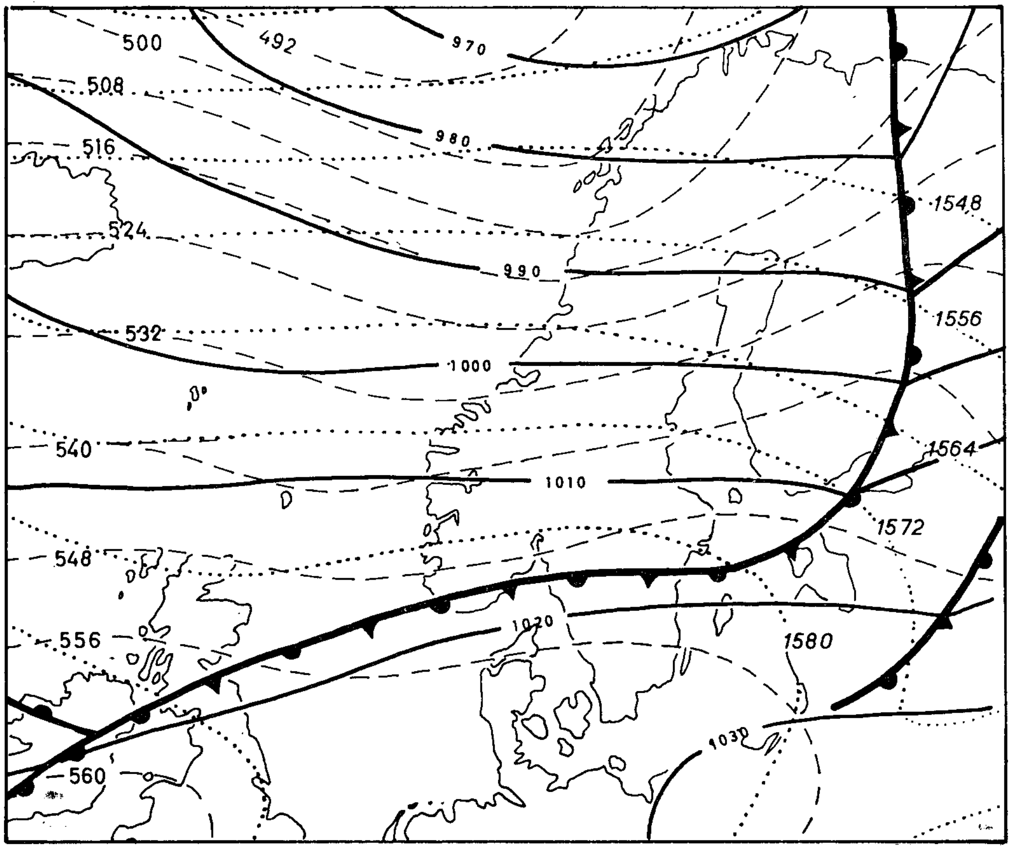

Fig. 5: Synoptic weather charts for 16th December 1957. Solid lines: surface chart 1500 GMT, broken lines: 500 mb contours 1200 GMT, dotted lines: 100 mb contours 0000 GMT. See also Figure 12.

Table 7. *Situation of mother of pearl clouds in relation to polar front waves.*

	S. Norway 1926—57		N. Scandinavia 1926—57	
	All observations	"Reliable" observations	All observations	"Reliable" observations
Far ahead of occlusion	2	—	—	—
Far ahead of warm front	2	2	1	1
Just ahead of occlusion	1	—	1	—
Just ahead of warm front	14	8	8	2
In the warm sector	28	20	9	3
Above occlusion	—	—	1	—
Just behind cold front	22	17	5	2
Just behind occlusion	2	2	5	2
Far behind cold front	10	8	7	4
Far behind occlusion	3	1	4	4
Not classified	6	—	2	—

wind ahead of the warm front the lower tropospheric clouds would not dissolve on the east side of the mountains, whilst with the usual W to NW-ly wind behind a cold front the frontal and post frontal clouds would be more easily dissipated by the mountains. Also by comparison with the cold front cloud system, the warm front clouds would usually cover an extensive area. Hence conditions favourable for viewing mother of pearl clouds would more often be post-cold frontal than pre-warm frontal.

Surface charts for some typical mother of pearl cloud situations are shown in Figures 2—5.

7. Upper wind direction and mother of pearl clouds. Observations of upper winds from the Norwegian Radiosonde stations were begun in 1946, and since 1949 fairly continuous observations have been made. However, in only 10 situations (all since 1949) has it been possible to use direct observations of upper winds in mother of pearl cloud situations. Since 1946, 22 cases of mother of pearl clouds have occurred, (neglecting the two summer situations mentioned in the preceding section), and, in order to treat them with some degree of uniformity, a study has been made of the relevant upper wind observations for Lerwick (making allowance for the movement of the synoptic system associated with the clouds).

Among the 6-hourly wind observations it was usually possible to find one and sometimes two which fitted well with the time of the observation of mother of pearl clouds. Table 8 shows the results so obtained.

An interesting feature of Table 8 is the constancy of wind direction with height; in the 22 situations the direction varied within 30° in 22 cases, within 20° in 20 cases

Table 8. *Upper wind directions during occurrence of mother of pearl clouds in Southern Norway 1946—57.*

Direction (±5°)	Southern Norway		Extrapolated Lerwick data				
	Geostrophic wind direction on the surface chart	Geostrophic wind direction on the 500mb chart	700 mb	500 mb	300 mb	200 mb	100 mb
240°				1	2	2	1
250°			4	4	1		1
260°	1	2	2	1	2	2	2
270°	1	2	4	2	3	2	
280°	3	3	6	5	5	5	4
290°	4	3	1	4	3	1	2
300°	4				1	2	1
310°	4	3	1			1	2
320°	1	6	2	3	4	3	2
330°		1	1	1			
340°	1	2	1			1	1
350°	1			1	1		
360°	2						

Table 9. *Geostrophic wind directions on the surface chart during occurrence of mother of pearl clouds.*

Direction (± 5°)	Southern Norway 1926—57		Northern Scandinavia 1926—57	
	All observations	"Reliable" observations	All observations	"Reliable" observations
100°	1			
130°			2	
180°	2		1	1
190°	1			
230°	1		2	
240°			1	
250°	1	1	2	
260°	5	2	2	1
270°	2	1	4	1
280°	6	3	3	1
290°	13	9	5	1
300°	10	9	4	2
310°	13	9	7	4
320°	5	5	4	3
330°	6	3	1	
340°	6	4	2	2
350°	2	1		
360°	6	5	2	1
Not classified	4			

and within 10° in 14 cases; it was constant in 3 cases. An approximate constancy of wind direction with height is an important feature in the theory of mountain wave formation.

Although it is reasonable to assume, considering the usual synoptic sequence in mother of pearl cloud situations, that constancy of wind direction with height over Lerwick implies a similar state of affairs over Southern Norway at some later time, it is not reasonable to assume anything about actual wind directions, and the most frequent wind direction in mother of pearl cloud situations cannot be deduced from the Lerwick data in Table 8 without a closer study. Upper air charts up to 100 mb are not available in Norway, but assuming the constancy of wind direction with height to exist over Southern Norway as well as over Lerwick, a study of the 500 mb wind directions would give a frequency distribution which is fairly representative even for higher levels.

The second column of Table 8, giving the geostrophie 500 mb wind over Southern Norway during the occurrence of mother of pearl clouds, shows features very similar to the Lerwick data, i.e. two maxima at 270° and 320° with a mean at 300°.

In order to increase the number of observations used and also to test the representativeness of the foregoing 22 observations, the concept of constancy of wind direction with height was extended and a study of surface geostrophic wind directions was made.

Table 9 shows the resultant distribution for all situations since 1926. The high frequencies for directions 290° — 300° — 310° are noteworthy. For Southern Norway these directions contained 42,9% of all situations (51,9% if we consider only "reliable" observations) and the "reliable" situations all lay within the sector 250°—360°. Among the remaining situations 4 could not be classified whilst still 4 cases fell so far outside the favourable range as to be regarded as suspect. It should be noted that 5 of these situations did not fulfil the criterion of the previous section, and all 8 were reported by unqualified observers and never by two observers simultaneously: all 8 situations have, therefore, been regarded as being very doubtful.

For Northern Scandinavia the results were, in general, similar to those for Southern Norway, wind directions around 310° being preferred. However, the small number of observations did not permit any more definite conclusions to be drawn. The representativeness of the observations from 1946—57 and consequently the validity of the deductions concerning variation of wind direction with height, may be seen by comparing the distributions of surface geostrophic winds shown in Tables 8 and 9; these are not essentially dissimilar.

8. Variation of wind speed with height. The lack of good upper wind observations from Norway has made it difficult to obtain typical wind profiles in mother of pearl cloud situations, and the conclusions of this section must necessarily be treated with some reservation. In most cases the Lerwick observations were used. Because extrapolation in distance and time is in general subjective, it was only possible to obtain broad general features. Although, in recent years, it has been possible to obtain observations from Sola and Gardermoen, these were often not self consistent and each station often gave an essentially different profile. Even though the methods employed to obtain wind profiles were unsatisfactory, certain common features have come to light: an increase in wind up to about 280 mb (9,5 km) being the most marked. The mean value of the maximum wind speed was about 105 kts. With such strong winds large variations in speed both horizontally and vertically would entail considerable errors in the estimation of a wind profile for any particular case even if reliable observations from Sola and Gardermoen were available. At the "standard levels" the estimated mean wind speeds were: 700 mb: 44 kts, 500 mb: 66 kts, 300 mb: 89 kts, 200 mb: 80 kts and 100 mb: 51 kts.

In a few cases the wind speed was nearly constant with height not exceeding about 50 kts.

Foldvik and Palm [8], using a wind profile with a typical maximum, calculated theoretical possible wavelengths which agreed well with some of the observed values. It would be of interest to repeat the calculations with other types of wind profile.

9. Mother of pearl clouds in relation to the height and temperature of the tropopause. It has been shown (section 6) that the occurrence of mother of pearl clouds is almost equally related to tropical and polar air masses; therefore, it should not be expected that representative mean values exist of temperature and height of tropopause. There should be, as was in fact found, two peak values for each parameter corresponding to situations of clouds forming over a tropical or a polar troposphere. In Figure 6 temperature has been plotted against pressure for 18 situations since 1946; 4 situations 1946—48 were omitted due to the absence of representative observations.

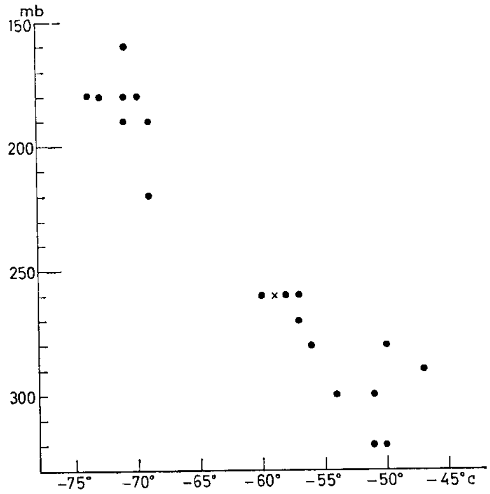

Fig. 6: Scatter diagram for pressure and temperature in the tropopause in mother of pearl cloud situations. The mean value for Lerwick is denoted by x.

In 8 cases, all referring to tropical air, the tropopause was colder (about 12°C in the mean) and higher (about 2,5 km in the mean) than the mean values for the season (represented by the point X). The remaining 10 situations, corresponding to polar air, had tropopauses warmer and lower than the mean (4°C and 1 km respectively in the mean).

It is of interest to note that the formation of mother of pearl clouds is not strongly dependent on the temperature profile below 15 km. Mother of pearl clouds seem to form equally well in tropical and polar air masses with high (cold) and low (warm) tropopauses. Calculations of the mean vertical temperature gradients above 1,5 km in the troposphere gave values ranging from 0,57 to 0,75°C/100 m, i.e. covering almost completely the range of mean gradients occurring in the troposphere.

Although a satisfactory determination of the vertical temperature gradients is very difficult, and the radiosonde stations used (Lerwick, Sola, Gardermoen, Gøteborg) often give quite different values, it is evident that mother of pearl cloud formation is apparently independent of trophospheric vertical temperature gradients.

10. Humidity in the stratosphere. Until Størmer's height determinations, in 1926, most meteorologists were of the opinion that stratospheric relative humidities were too low to permit cloud formation. Even after Størmer's work many meteorologists considered that the clouds consisted of other substances, such as carbon dioxide, and not water. Measurements of humidity in the stratosphere have only been made since the second world war. Observations from England [14, 15] have shown that the relative humidity is generally very low; a series of 80 observations at 13,5—15 km gave a mean value of $R_i = 2{,}3\%$, R_i being the relative humidity with respect to ice.

Occasionally, considerably higher values have been obtained, but, whilst these may be used to obtain an idea as to possible magnitudes of stratospheric relative humidity, insufficient data exist for a study of variations in humidity and the origin of such high values. The observations from England have been made up to 15 km, i.e.

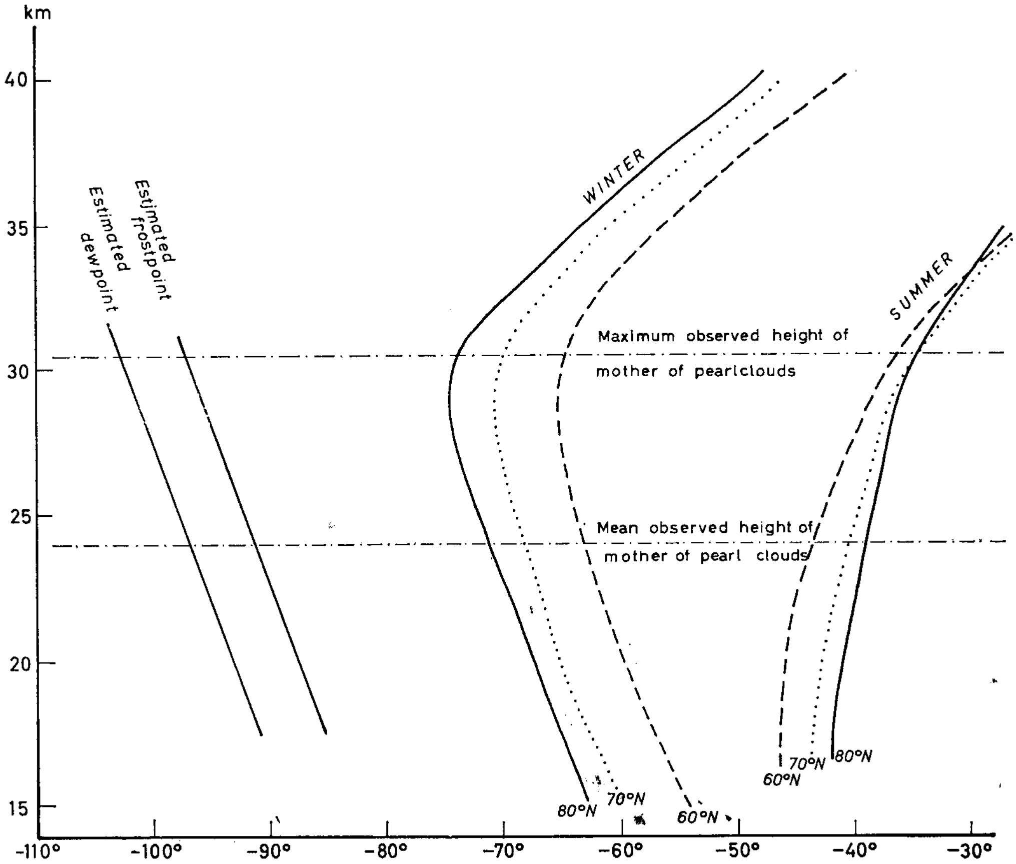

Fig. 7: Estimated frostpoints and dewpoints in the stratosphere compared with mean temperatures for winter and summer.

to about 4 km above the tropopause. A study of the mixing ratio above the tropopause showed a rapid decrease with height in the first 1—2 km, with, at greater heights, a convergence to values which change little from one situation to the next. It will be assumed below that no sources and sinks of water vapour exist at the levels of mother of pearl cloud formation. Under such circumstances it would appear reasonable to assume that the mixing ratio should remain constant up to the level at which mother of pearl clouds form.

Neglecting two observations of unusually high values of the mixing ratio, 67 observations gave a mean value of $0{,}167 \cdot 10^{-2}$ gr/kg with a standard deviation of $0{,}060 \cdot 10^{-2}$ gr/kg. With the mean value of the mixing ratio frostpoints have been computed and to a sufficient degree of accuracy, the dewpoints have been estimated for heights up to 30—35 km. The results are shown in Figure 7. Variations of mixing ratio with the limits of its standard deviation gave variations of frostpoint and dewpoint of about 2°C. At 25 mb (about 24 km) the mean frostpoint would be ÷92,0°C with upper and lower limits of ÷90,3°C and ÷94,3°C.

Figure 7 shows that cloud formation at 20—30 km would only occur in the presence of exceptionally low temperatures, ÷90°C to ÷100°C. Such temperatures do not generally occur, but may, perhaps, be produced by local vertical displacements, for example, in connection with mountain waves.

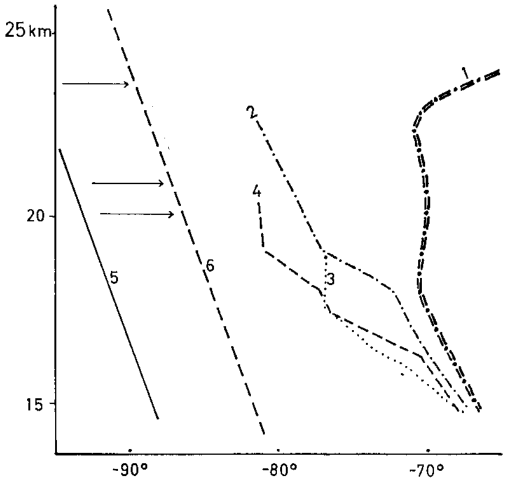

Fig. 8: Description of the upper air temperature conditions 29th February 1956, (1: Alert 1500 GMT 26th February, 2: Lerwick 1400 GMT 29th February, 3: Stockholm 1400 GMT 29th February, 4: Gøteborg 1500 GMT 29th February, 5: estimated dewpoint, 6: estimated frostpoint.) The arrows indicate measured heights of mother of pearl clouds.

11. Mother of pearl clouds and stratospheric temperatures. The very first measurement of stratospheric temperature in mother of pearl cloud situations indicated the presence of abnormally low temperatures. With the recently improved upper air network it has been possible to study the behaviour of stratospheric temperatures in some detail. Using observations from Lerwick and, in later years, from Sola, Gardermoen, Gøteborg and Stockholm, it has been possible to obtain representative values of temperature at 100 mb and 60 mb in mother of pearl cloud situations. In 21 (out of 22) cases the temperatures were significantly lower (about 10°C) than the seasonal mean. The one remaining situation ("non-reliable") gave temperature 10°C above the mean for the season and is probably an observational mistake.

For the 21 situations mean temperatures at 100 mb and 60 mb were ÷67°C and ÷69,6°C respectively; using only observations since 1950 the corresponding values were ÷68,3°C and ÷72°C. Due to lack of observations no mean values have been computed for levels above 60 mb. Occasionally soundings have been made to greater heights. Some of these are shown in Figure 8.

In order to study the temperature conditions at higher levels the mean temperature profile as computed by Murgatroyd [7] is shown for 60°, 70° and 80°N for summer and winter seasons. Comparison between these curves and the dewpoint curve shows, as was shown statistically in section 2, that mother of pearl clouds are much more unlikely in summer than in winter. During the summer the difference between temperature and dewpoint is about 50°C at 20 km increasing to 65°C at 30 km, and, as deviations from the mean temperature are generally small in summer, a local cooling sufficient to cause condensation would hardly ever occur. During the winter the difference between mean temperature and dewpoint is about 25—30°C and in mother of pearl cloud situations the difference was usually about 15—20°C at about 20 km. As the vertical temperature gradient above 20 km seems to be greater than the decrease

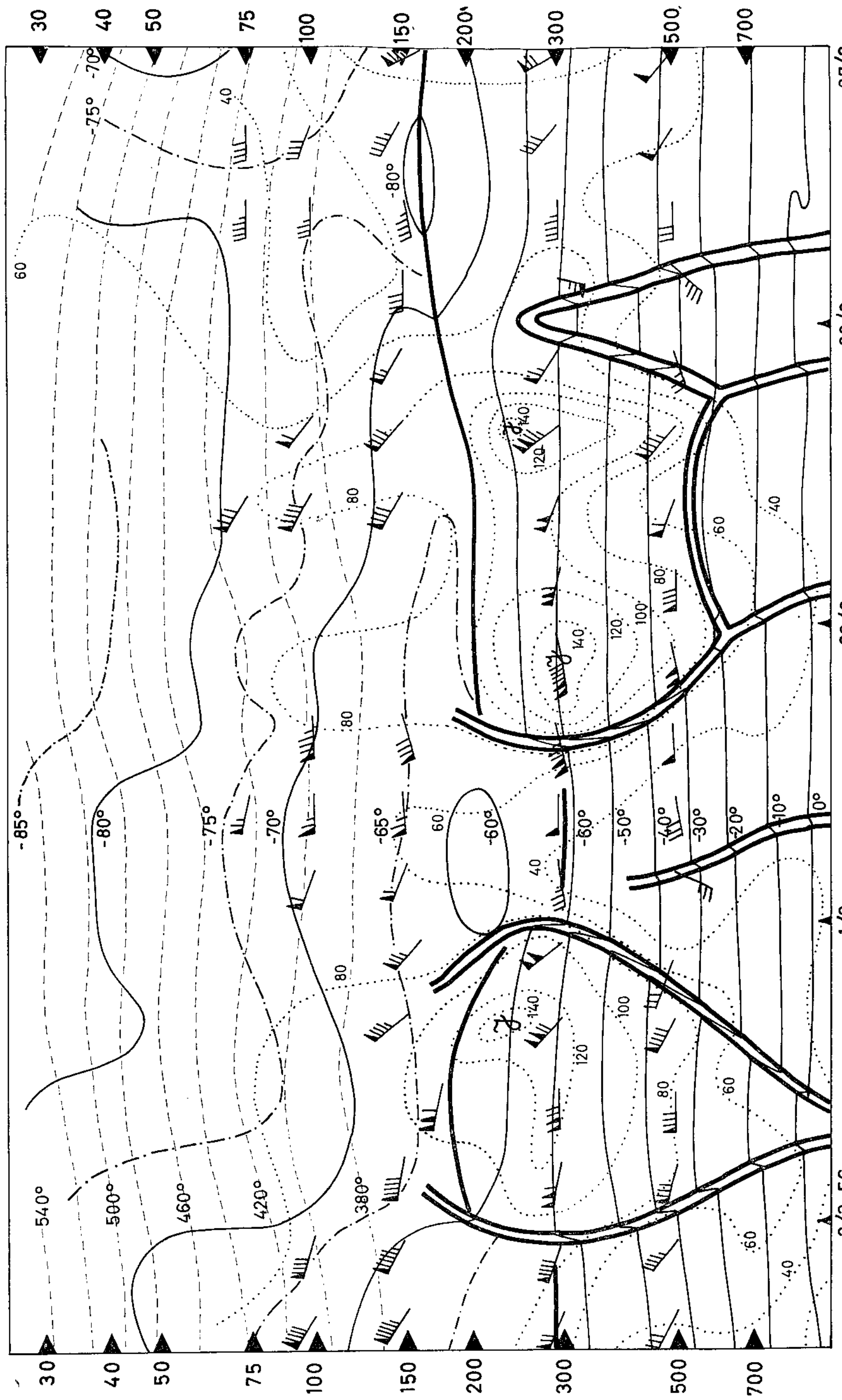

Fig. 9: Vertical time cross-section for Lerwick 27th February—2nd March 1956. (Thick lines: fronts and tropopauses, thin lines: isotherms drawn with 10°C intervals, dash-dotted lines: intermediate isotherms in the stratosphere, broken lines: isentropics, dotted lines: isovels drawn with 20 kts intervals.) Mother of pearl clouds were observed in Southern Norway 1200—1700 GMT 29th February at a height of 20—23,5 km. See also Figure 2.

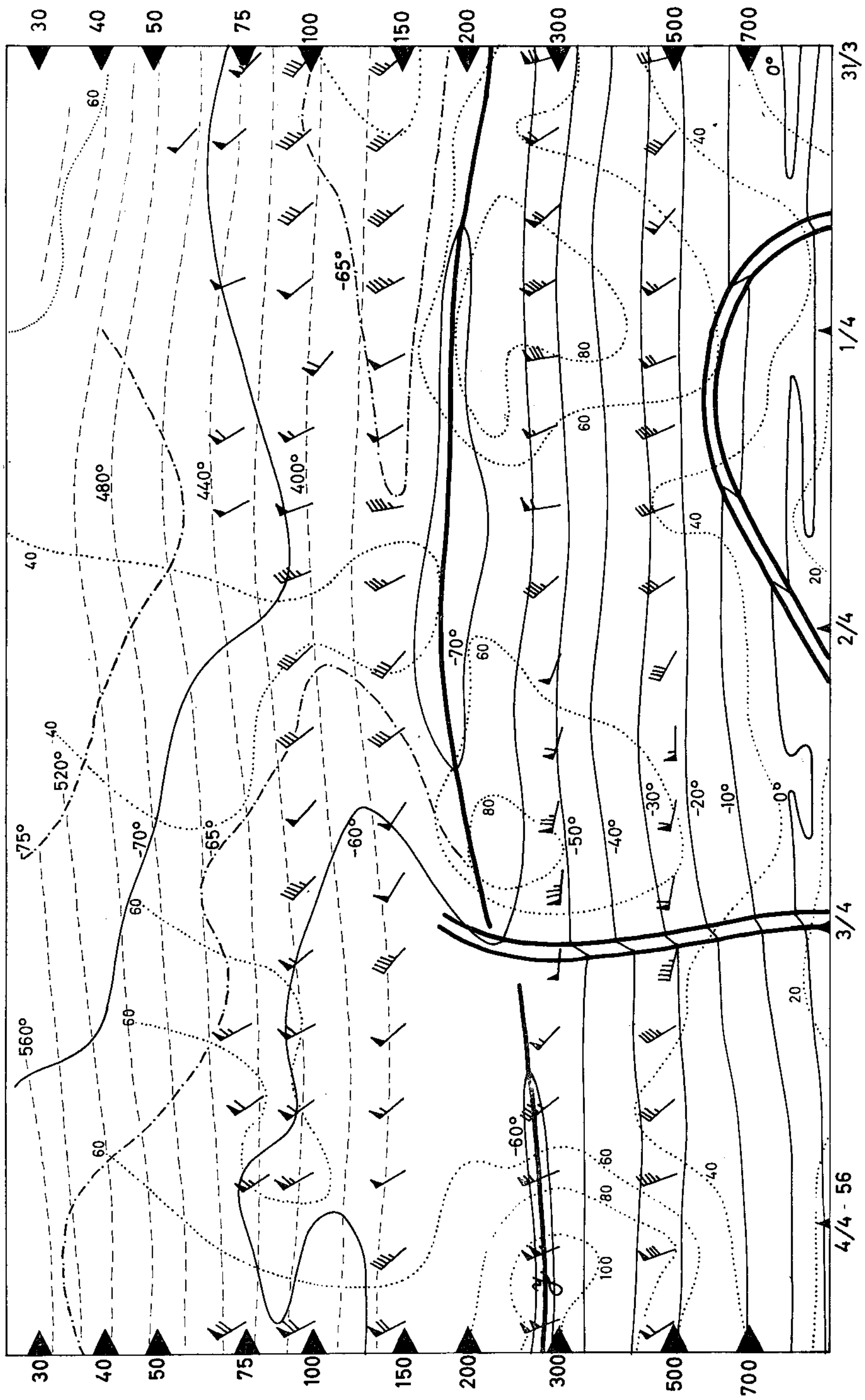

Fig. 10: Vertical time cross-section for Lerwick 31st March—4th April 1956. Mother of pearl clouds were observed over Southern Norway 2nd April about noon. See also Figure 3.

Fig. 10: Vertical time cross-section for Lerwick 31st March—4th April 1956. Mother of pearl clouds were observed over Southern Norway 2nd April about noon. See also Figure 3.

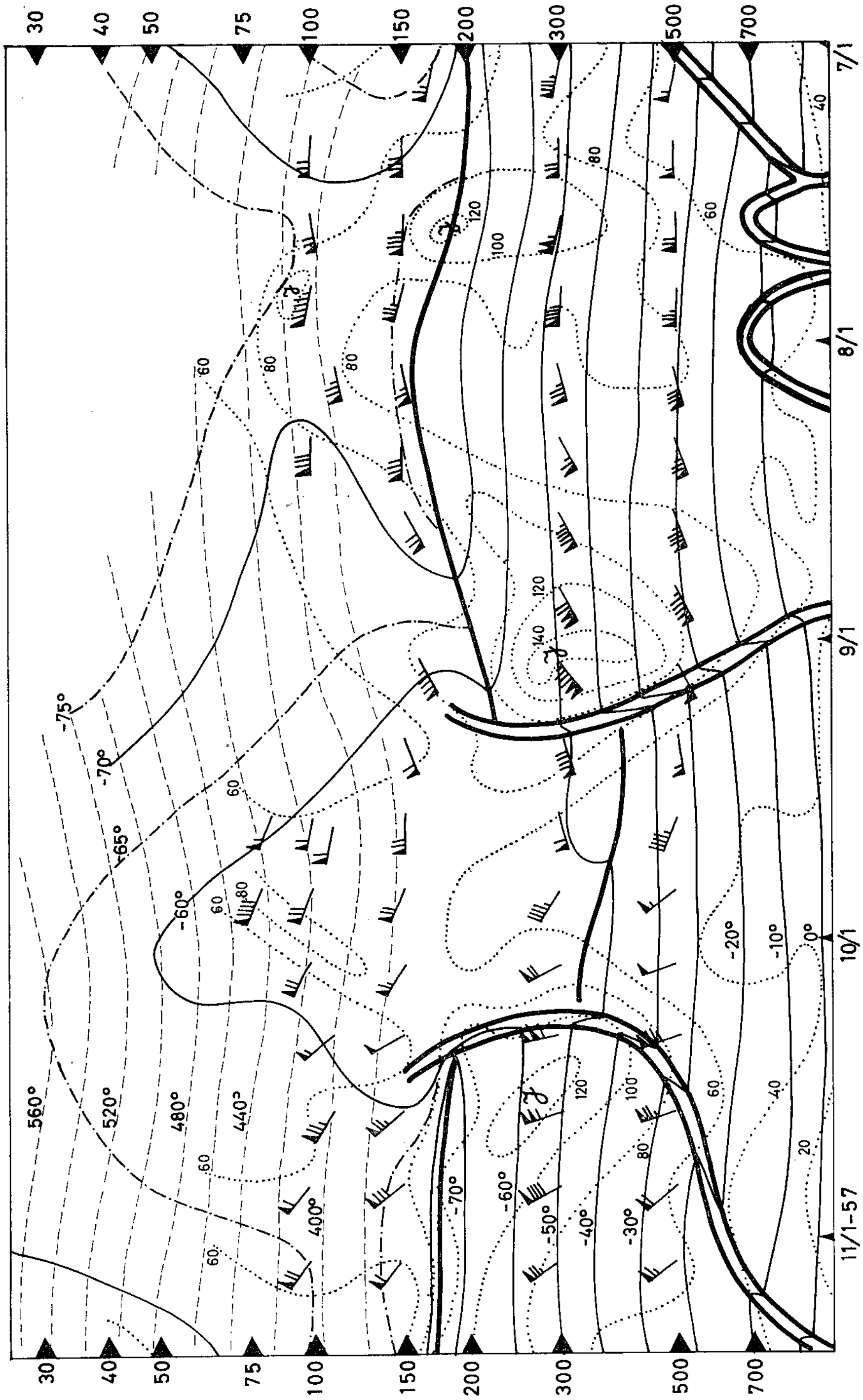

Fig. 11: Vertical time cross-section for Lerwick 7th—11th January 1957. Mother of pearl clouds were observed over Southern Norway 0800—1500 GMT 9th January 1957. See also Figure 4.

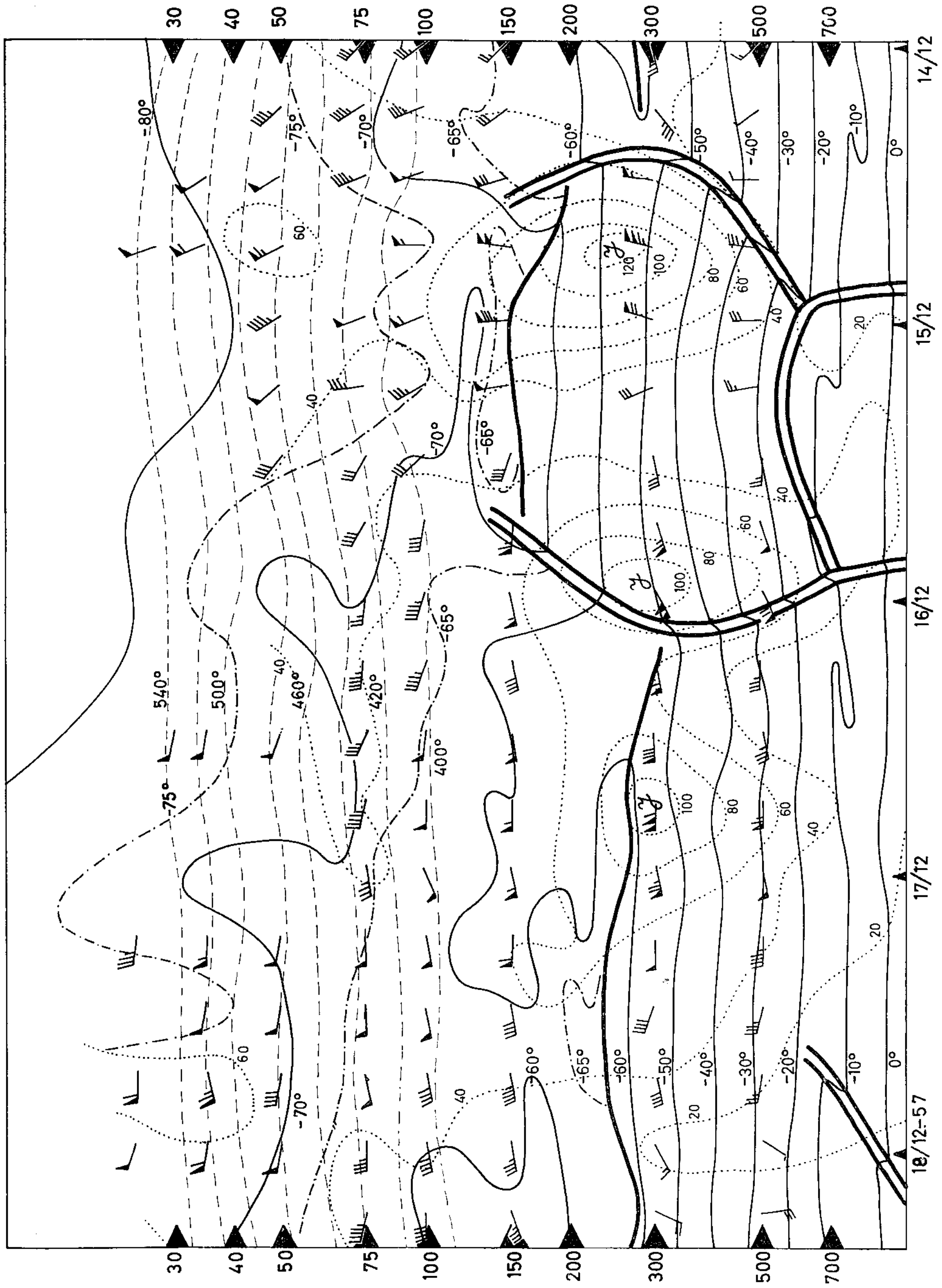

Fig. 12: Vertical time cross-section for Lerwick 14th—18th December 1957. Mother of pearl clouds were observed over Southern Norway 1500 GMT 16th December. See also Figure 5.

of the dewpoint with height, the spread is likely to decrease up to the usual level of mother of pearl cloud formation.

Above 30 km the difference between temperature and dewpoint increases so as to make condensation above 30 km unlikely throughout the whole year. This agrees well with Table 4, where the highest mother of pearl cloud recorded is shown to be 30.6 km.

The temperature conditions in four mother of pearl cloud situations are shown in Figures 9—12.

12. Droplet sizes in mother of pearl clouds. It is generally accepted that mother of pearl clouds form as drops of water, but concerning their transformation into ice very little is known. Mason [16] suggests that the condensate may be "vitreous ice" which crystallizes slowly and remains spherical. If the cloud particles did become ice during their short lifetime then the clouds should have an asymmetric shape with an ice tail in their downwind parts. Even if tails of great horizontal extent have been seen in mother of pearl clouds, the clouds have generally been of a symmetrical appearance, showing that the cloud particles remain liquid (or possibly vitreous ice).

Due to the great height of the clouds no direct measurements of drop size have been made. However, considering the iridescence as parts of coronae, the optical method used in aureole measurements has been used[1]. In the formula

$$\sin \varphi_1 = 1.22 \frac{\lambda}{a}$$

(φ_1 = angular distance from light source to minimum intensity of wavelength λ, a = droplet diameter), it is generally assumed that $\lambda = 0.57\mu$ for aureole measurements, referring to the outer ring of the corona. However, in the case of mother of pearl clouds, with their brilliant iridescence, the droplets are so uniform that it is possible to use the formula for monochromatic light, thus differentiating between the colours, and make more accurate estimates. In the following, the formula

$$\sin \varphi_2 = 1.64 \frac{\lambda}{a}$$

has been used (φ_2 = angular distance from light source to maximum intensity of wavelength λ). In a case when a corona with distinct colours was observed around the moon [4], Størmer found $a = 2.5\mu$ using the formula for minimum intensity. The formula for monochromatic light gives a somewhat greater value for the diameter: $a = 3.7\mu$ was found for the yellow ring and $a = 3.7\mu \pm 0.2\mu$ for the red ring.

In one of his papers [10], Størmer has reproduced a drawing of a mother of pearl cloud, giving the distribution of the colours and a scale for azimuth and elevation.

[1] Note added in the proof: Professor Høiland has drawn my attention to a section of a paper by H. Weickmann: Die Eisphase in der Atmosphäre (Berichte des Deutschen Wetterdienstes in der US-Zone, Nr. 6), 1949, where he gives a theory for the iridescence based upon a practical and theoretical work by Mecke.

This cloud had a typical lenticular form. From the given data, the size of the droplets has been found for different parts of the clouds. In the western part, where the droplets entered the cloud, the diameter was found to be 2.3μ with a continuous increase to 3.3μ in the eastern part of the cloud. Another very thin cloud on the same drawing had a droplet size of 1.9μ. From another drawing, droplet sizes from 1.5μ to 2.8μ were found, but this situation was not as suitable for droplet size determinations as the former.

It has been pointed out by many authors that, for diameters below 10μ, there is some discrepancy between observed droplet sizes and the values found by means of the formula. For diameters less than 2μ it has been found that the theory is no longer valid. But it is believed that the results obtained in this section represent good approximations as to the size of the particles of mother of pearl clouds.

Iridescence is also, at times, observed in tropospheric clouds but only rarely as brilliantly as in mother of pearl clouds. In tropospheric clouds droplets are somewhat greater than those deduced for mother of pearl clouds; typical droplet mode diameters are 8μ in stratocumulus and 15μ in large cumulus. For red light, and droplets greater than 8μ, iridescence can only occur at angular distances less than $6\frac{1}{2}°$ from the sun, and less than $4^{3}/_{4}°$ for green light. For such small angular distances from the sun, account must be taken of the finite extension of the light source, and distinct colours can no longer be expected. In addition, the droplet size spectrum in tropospheric clouds is, in general, broad with a resultant reduction in the brilliance of the iridescence. In tropospheric clouds, therefore, iridescence can only be expected in clouds with unusually small droplets. This will sometimes occur in lenticular clouds or in fragments of high altocumulus. In the latter case faint red and green colours occur. In the case of lenticular clouds the droplets are small and almost uniform in size and consequently brilliant colours may at times be seen; such clouds have often been mistaken for genuine mother of pearl clouds.

12. Liquid water content and concentration of droplets in mother of pearl clouds. If we assume that the air at the levels of mother of pearl clouds contains sufficiently high concentrations of condensation nuclei, calculations can be made of the liquid water content and the numbers of cloud particles in mother of pearl clouds.

Using the dewpoint and diameters ($a \approx 3\mu$) obtained in the foregoing sections results are shown in Table 10 for height of 20, 24 and 30 km and for displacements of 100—500 m above the condensation level. As might have been expected, the liquid water content is much lower, by a factor of 10^3 — 10^4, than in tropospheric clouds, and the numbers of drops smaller by a factor of $10 — 5 \cdot 10^2$.

However, recent measurements of the concentrations of condensation nuclei in the upper troposphere indicate that the concentrations of nuclei at the levels of mother of pearl clouds are probably lower than the numbers of cloud droplets given in Table 10. This means that all condensation nuclei are used at the initial stage of the cloud formation. All droplets will therefore start their growth at the same time and tend to be equally sized. This would explain the brilliant iridescence generally observed.

Table 10. *Estimates of liquid water content and concentration of cloud particles in mother of pearl clouds.*

Vertical displacement above condensation level	Liquid water content gr/m³			Number of cloud particles pr. cm³		
	20 km	24 km	30 km	20 km	24 km	30 km
100 m	$2,2 \cdot 10^{-5}$	$1,2 \cdot 10^{-5}$	$0,5 \cdot 10^{-5}$	1,6	0,8	0,4
200 m	$4,2 \cdot 10^{-5}$	$2,2 \cdot 10^{-5}$	$0,9 \cdot 10^{-5}$	3,0	1,6	0,6
300 m	$5,7 \cdot 10^{-5}$	$3,1 \cdot 10^{-5}$		4,0	2,2	
400 m	$6,9 \cdot 10^{-5}$	$3,7 \cdot 10^{-5}$		4,9	2,6	
500 m	$8,0 \cdot 10^{-5}$	$4,3 \cdot 10^{-5}$		5,7	3,0	

In clear stratospheric air supersaturation with respect to water would be necessary to ensure cloud formation. At the temperatures prevailing at mother of pearl cloud levels the difference between dewpoint and frostpoint is about 3,5°C. With such great differences, supersaturation with regard to ice and subsaturation with regard to water are possible over large areas. Under such conditions it might be possible that a few scattered ice crystals would result to give a thin, almost invisible veil. Such veils have been observed before sunrise and after sunset. It has sometimes been reported in mother of pearl cloud situations that the twilight had a peculiar colour. Two observers report that before sunrise the sunlight was green or yellow-green, and that objects illuminated by indirect sunlight had a green appearance. A third observer stated that the twilight gradually changed from red to green and blue, whilst a fourth reported mountain snow with a sharp blue colour. Such colours were due to changed scattering properties of the atmosphere, and may have been caused by the slow crystallization of minute ice particles in air supersaturated with respect to ice, but subsaturated with respect to water. The author has observed that on some occasions the sky has obviously been covered by an extensive, thin veil, only detectable near sunset when the sky was of uneven brightness due to faint shadows from thicker parts of the veil.

Clouds of a similar character (stratospheric cirrus) have been reported from the Antarctic by Liljequist [17]. The temperatures in the Antarctic winter stratosphere are somewhat lower than the corresponding temperatures in the Arctic winter stratosphere. Assuming the humidity conditions to be the same in both hemispheres, supersaturations in the stratosphere are likely to occur much more often in the southern than in the northern hemisphere.

Concluding remarks. It has been shown that, even in the Arctic during winter, cloud formation is in general impossible between 20 and 30 kms except in the presence of extreme, possibly very local cooling.

In mother of pearl cloud situations upper air soundings have in general shown temperatures well above the dewpoint. The possibility of the existence of cold air masses of small horizontal extent cannot be excluded. Reports of mother of pearl clouds lasting several days and existing over large areas, — e. g. 5th February 1934 (Aberdeen, Oslo and Finmark) and 16th January 1958 (Oslo and Alta) — make it, however, unlikely that the formation of the clouds is dependent on such small areas of cold air.

Stratospheric temperatures in mother of pearl cloud situations have been shown to be significantly lower than the seasonal normals. It is suggested that this is a result of advection of Arctic stratospheric air and this suggestion is supported by a study of 100 mb charts. It is of interest to note that the temperatures of cold domes of Arctic air often decrease as the air moves SE; this cooling is of the order 10—15° and is presumably due to lifting as the stratospheric air approaches and overruns a tropospherical frontal cyclone. In such a manner it is possible for temperatures of ÷80°C — ÷90°C to be produced at 25 kms, a further cooling of the order of 10°C being necessary to the formation of clouds. As mountain waves have been observed to have amplitudes of 750 m at or near the tropopause [9], and as condensation could occur with only slightly smaller amplitudes, it is suggested that local lifting due to mountain lee waves could give the additional cooling needed for the formation of mother of pearl clouds. The difference between temperature and dewpoint in the stratosphere is usually at a minimum just below the marked inversion at 23—30 kms and it is near these levels that the clouds usually form.

The ideas developed above have been based upon relatively few observational facts. A detailed analysis of some recent mother of pearl cloud situations has been started, and it is believed that observations from the improved upper air network during the International Geophysical year will provide valuable information on the formation of the clouds and related problems.

Acknowledgements. The author wishes to express his gratitude to the late Professor Carl Størmer who always showed very great interest in the work. Without the permission to use his observational data the preparation of this paper would have been impossible.

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