Experimental Study of Mountain Lee-Waves by Means of Satellite Photograph and Aircraft Measurements

By Dr. Denise Cruette, University of Paris VI

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Abstract

This paper is a summary of an extensive systematic study (1) of the influence of various meteorological factors on the occurrence and characteristics of mountain waves, more specially the lee-waves of great horizontal extent. The data used are, beside classical meteorological informations, those given by satellite pictures completed by quasi-simultaneous measurements from aeroplanes or gliders.

The analysis of many satellite pictures received at the French station of Lannion (Brittany) during a period of three years (1966–1968), gave a fairly complete description of lee-wave clouds visible over Western Europe and North Africa, and led to the following conclusions:

(i) In all the cases of lee-waves that were considered, a layer with a great static stability was recorded between 1 000 and 4 000 m above sea level.

(ii) The horizontal extent of the lee-waves was found to vary in inverse ratio of the thickness of this highly stable layer, which thus appears as a wave guide where almost all the energy of the mountain perturbation is «trapped», in the same way as along the free surface of a quiet sheet of water where ordinary gravity-waves are produced (category of the so-called «surface waves»).

1. Introduction

It is well known that a wind crossing a mountain range frequently produces a system of nearly stationary lee-waves if both its speed and static stability have a proper vertical distribution. These lee-waves were brought to evidence by glider pilots, and their study gave rise to many theoretical and experimental researches; however, although their discovery now goes back almost half a century, the process of their formation is still far from being completely elucidated.

From 1960 onwards, pictures supplied by satellites revealed the relatively frequent occurrence of remarkably regular and extended lee-waves clouds, most of them downwind from great mountains (Andes, Rockies), but some of them also in the lee of moderately mountainous islands (as shown on Fig. 1).

The knowledge of such a great extent was really a new fact, as well as the aparently comparable importance of lee-waves produced by mountains very different in scale. But it remained to prove that all these waves could actually be considered as stationary ones.

In order to explain a great extent of lee-waves, three factors could be invoked, each of them accounting for a horizontal guiding of wave energy:

(i) A stable atmospheric layer in altitude, producing a reflection of the wave motion.

(ii) A large vertical gradient of the vertical wind shear near one level, of the type encountered in jet streams.

(iii) A large static stability concentrated near one level.

However the published studies relative to the phenomenon can hardly be considered as conclusive, since they all concerned individual cases, and in addition their authors recognized that they had not enough data in the vicinity of the observed waves. The present work is a systematic study using satellite photographs collected in France (at Lannion), as well as data given by balloons, aeroplanes or gliders.

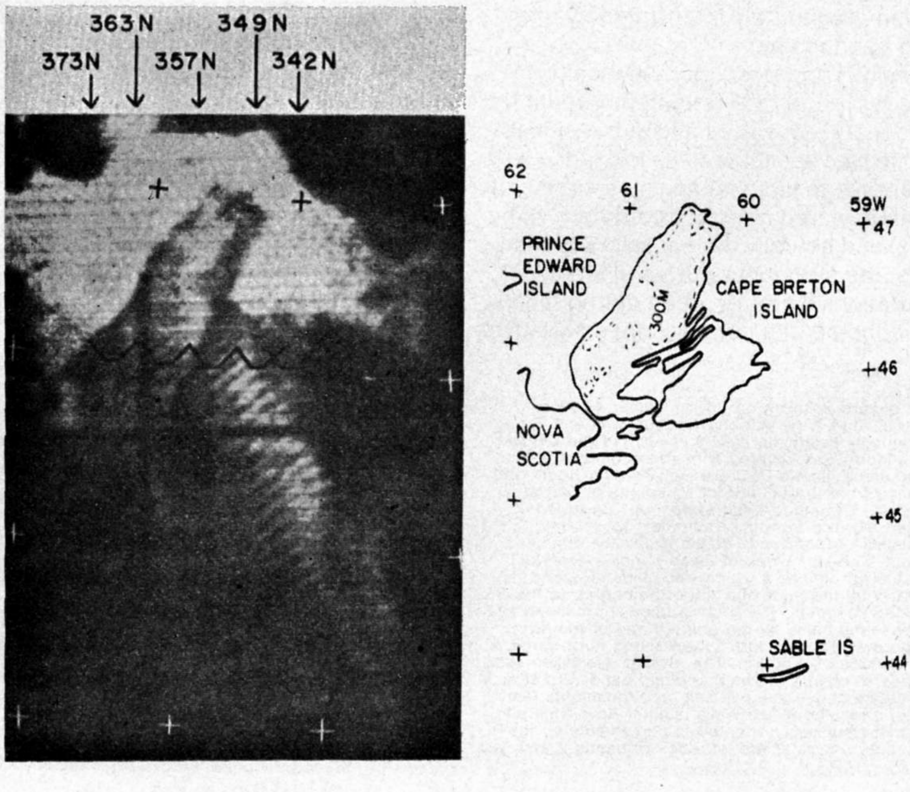


Fig. 1. Lee-wave cloud pattern downwind from Cape Breton Island (Canada).
This cloud system extends over 250 km downwind from the island, which culminates at an average altitude of 300 m.
Cloud band spacing is 8,3 km according to J. CONOVER (1964)

2. Working Methods

We first collected a great deal of data concerning the mountains waves in general, then we tried to complete the information given by satellites with quasi-simultaneous measurements from aeroplanes and gliders.

2.1. Collection and use of existing documentation

Immediately available information consisted mainly of daily pictures received from satellites at Lannion. However a systematic examination of so many pictures (about 7 000 for the three years 1966 to 1968) being practically impossible, we were led to make an inquiry in the form of a questionnaire sent to airline pilots, aero clubs, and also to French and Spanish gliding associations for whose pilots wave flights are common.

We thus were able to select the interesting cases and, in addition, this inquiry provided us with very valuable complementary data. We examined satellite pictures for 562 days and found 277 cases of interest, distributed over 110 days and among which only 26 cases were related to lee-waves located in the close vicinity of areas where gliders had operated. For all the 110 days the meteorological documents available from the French weather services (weather maps, soundings and daily reports) were collected and analysed.

2.2. Additional measurements

Information on the detailed distribution of hydrodynamical parameters, inside and around the systems of lee-waves, can be obtained by several techniques, which were tested in two preliminary investigations conducted in the Pyrenees with the French weather services, in February 1966 and November 1967. Each investigation involved substantial effort, both in personal (some thirty people) and in instrumentation (in particular: 2 aeroplanes, 3 to 5 gliders, 2 radars). The aeroplanes were used for recording pressure, temperature and humidity (vertical soundings, mainly), and with the gliders it was intended to develop a method for measuring the distributions of temperature and vertical air speed (see below). In addition some soundings were made by means of floating vehicles (balanced balloons) equipped with reflectors.

Several reasons justify the use of gliders: they have low sinking speed (45 to 75 cm/s), a very good response to vertical impulses, and owing to the lack of any vibration they make up excellent experimental platforms especially for measuring air temperature, at altitudes up to about 10 km. Of course a glider cannot be as easily utilized as a powered aircraft, but it is far easier to use than a balanced balloon, the launching of which under strong-wind conditions can prove difficult, if not impossible. Moreover with a balloon the trajectory is not easy to predict, the recovery is generally impossible, and the flight is often prematurely interrupted by frosting phenomena.

Finally it appeared that the ideal vehicle for recording instruments would be probably a powered glider, but since none was available to us in France we were led to make all the measurements with powered aircraft or ordinary gliders, and actually the majority with gliders: the air temperature and altitude variations were recorded during flights conducted at a constant speed relative

On picture 2, taken on 23 December 1969 at 11H09 G.M.T. by satellite Nimbus 3, A and B respectively designate the Pyrenees and the Cantabric Mountains covered with stratocumulus. Wave-type cloud visible in C are located over Spain and extend from the latitude of Pamplona to that of Madrid. The cloud band system visible in D is located leeward from the Espinouse Mountains. It consists of four bands distant from one another by about 13,5 km. Three of these bands are perfectly visible on picture 3 which was taken around 12H G.M.T. by the pilot of a glider belonging to the PEZENAS Aeroclub. The glider whose approximate position is indicated by the pointed end of the arrow we drew on the picture 2, was flying northwards, at an altitude of 4 500 m. The picture was taken eastwards. It clearly shows that cloud bands are stratocumulus; above one can see an altocumulus lenticularis located in the wave laminar flow. This altocumulus curiously oriented is perceivable on the satellite picture at the left edge of bands 2 and 3.

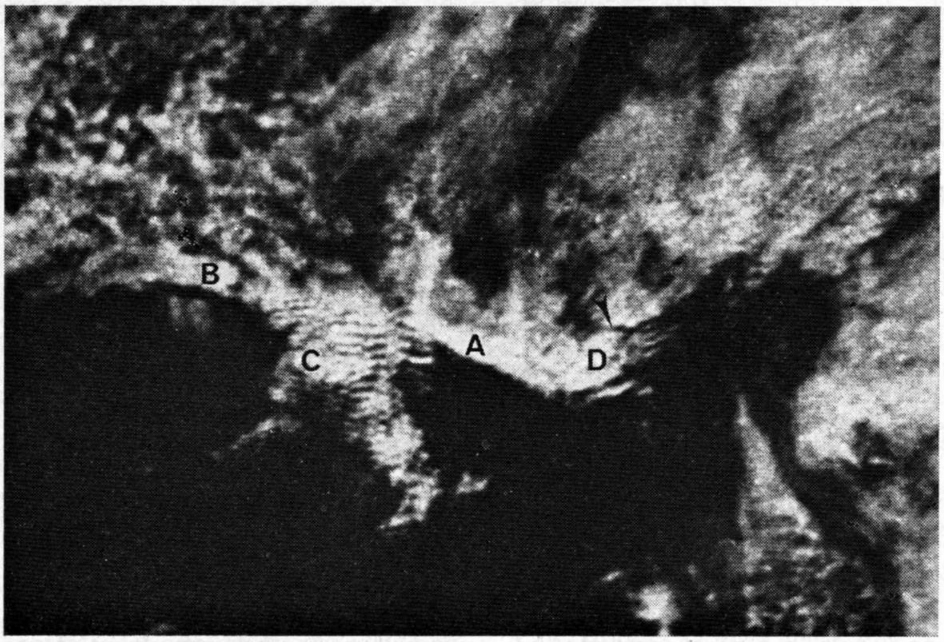


Fig. 2. 23 Dezember 1969 at 11H09 G.M.T.

Fig. 3. 23 December 1969 around 12H G.M.T.

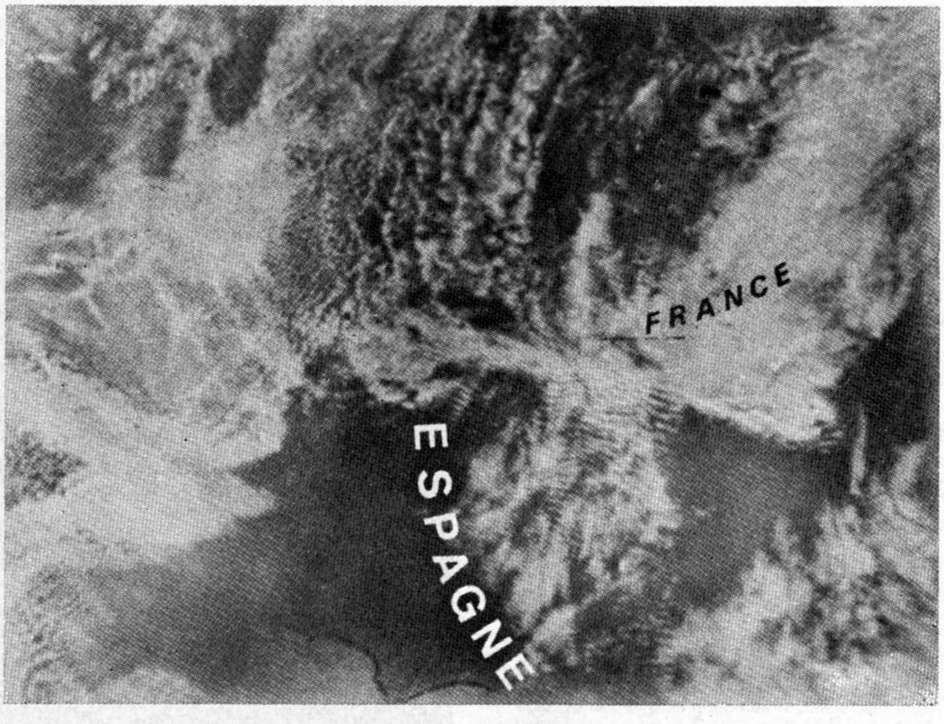


Fig. 4. Lee-wave cloud pattern over Spain. Cloud band spacing of about 18 km.
Nimbus 2-3340 8 December 1969 at 10H50 G.M.T. Photograph by Météorolie Nationale.

to the air and approximately parallel to the wind, either in the same direction (tailwind flights, where the recorded altitude variations are in phase with streamline waves) or in the opposite one (headwind flights, where altitude variations and streamline stand in opposition); then from these documents both the wavelength and amplitude of lee-waves could be deduced, at the same time as the vertical air speed (in the case of a glider flight, the vertical speed given by the altimeter curve had to be corrected for the descending speed of the vehicle, as measured in still-air conditions; the vertical air speed so obtained was probably correct within less than 20 cm/s).

According to satellite pictures the region of France where well-defined lee-waves are most likely to appear is the Lower Languedoc area (see § 3.1 below), and moreover it was particularly convenient for our experiments since it is quite close to the National Gliding Center of «La Montagne Noire» (midway between Toulouse and Montpellier), which could provide us with all its facilities and aircraft equipment.

Our main objective was to obtain data from aeroplanes or gliders at the same time as pictures received at Lannion would show the occurrence of wave clouds in the area, leeward from the Cevennes or Espinouse, and for this purpose an efficient system had to be set up, able to be put into operation at any time upon a mere telephone call. This system became operational from February to April 1969, then from December 1969 to February 1970, and on two occasions (during the second period) wave clouds over the Lower Languedoc could be photographed from aircraft less than one hour after their presence had been announced by Lannion (Fig. 2 and 3).

However the satellite pictures revealed only a few cases of lee-wave clouds over the area during these two periods: only 7, against more than 65 days of lee-waves occurrence as indicated by local observation (but the same satellite pictures often showed very noteworthy wavelike cloud bands over Spain; see Fig. 4).

3. Results for Western Europe and North Africa

The geographic area that we surveyed by means of satellite pictures is illustrated in Fig. 5. More precisely, as previously mentioned, 562 days were examined over a period extending from March 1966 to December 1968.

3.1. Main characteristics of wave clouds and associated motions

The analysis of satellite pictures enabled us to give a fairly detailed description of the lee-waves phenomenon: general aspect and horizontal dimensions (Fig. 6), spacing of cloud bands (Fig. 7), geographical distribution as a function of wind direction (Fig. 5) and of altitude of underlying area (table 1), seasonal variations (Fig. 8), etc.

In particular, this study showed that lee-wave clouds occur quite frequently, especially near mountains and in winter, and that there are certain favourable regions. Among them, let us mention the Lower Languedoc, in France, and the Upper Ebro Valley, in Spain, this latter area being often covered with lee-waves systems of very great extent and regularity (Fig. 2 and Fig. 4 are good examples), a rather surprising fact since it is a place where the WNW-ESE barrier formed by the Cantabric Mountains and Pyrenees subsides into a saddle about 150 km wide and 1 200 m. high. But there are other regions showing the same particularity, for instance the Alberic Mountains, at the eastern end of Pyrenees, which are apt to cause the formation of a system of waves over the flat Gerona country, these waves extending as far as the Mediterranean shore and sometimes even over the sea.

In order to determine the nature and altitude of the wave clouds, the process of their formation, their vertical extent, and also the direction and evolution of

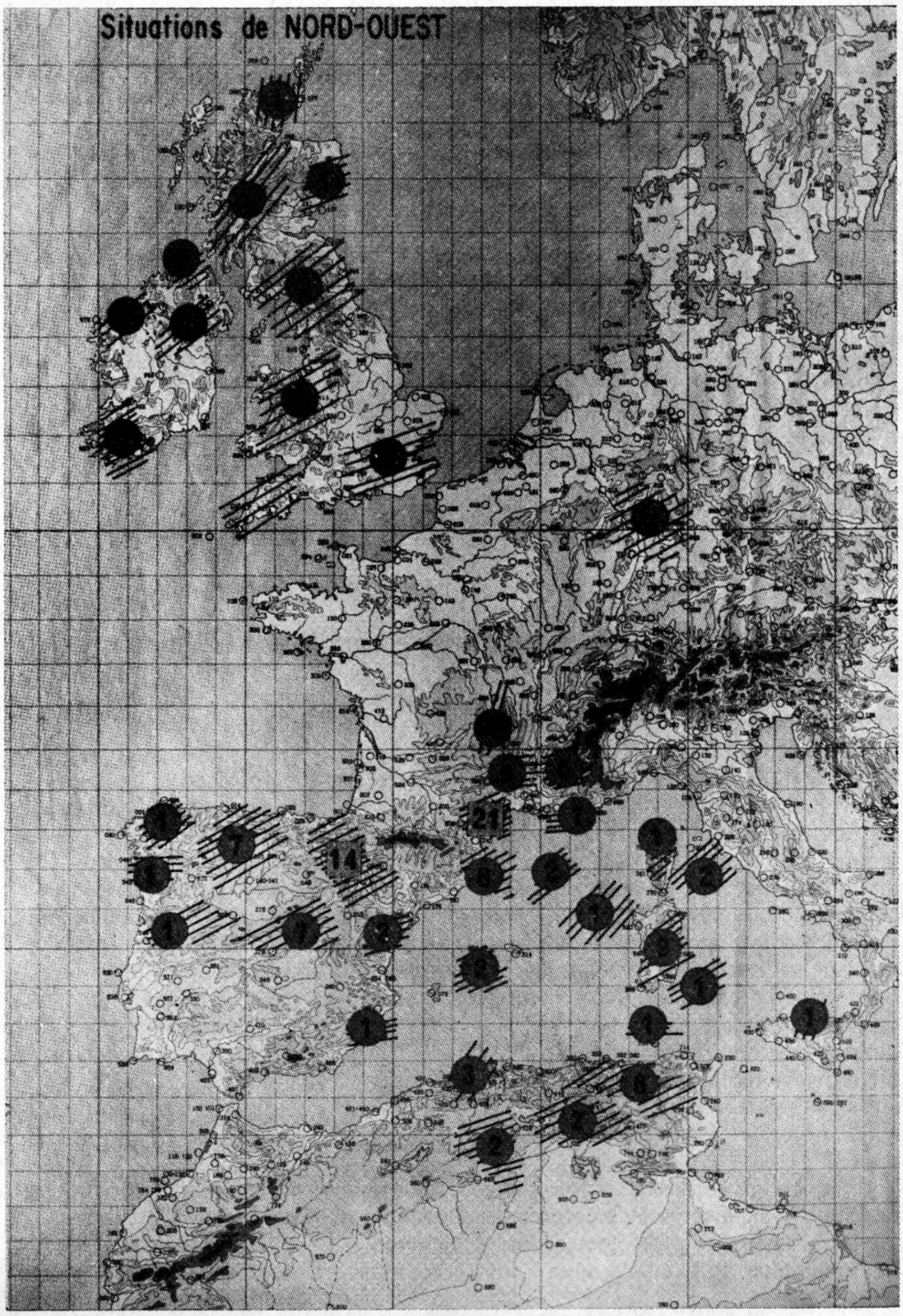


Fig. 5. Surveyed area. Shows geographical distribution of wave-type clouds under northwesterly wind. Numbers indicate how many loud systems were observed in each area for the period between 3 March 1966 and 31 December 1968.

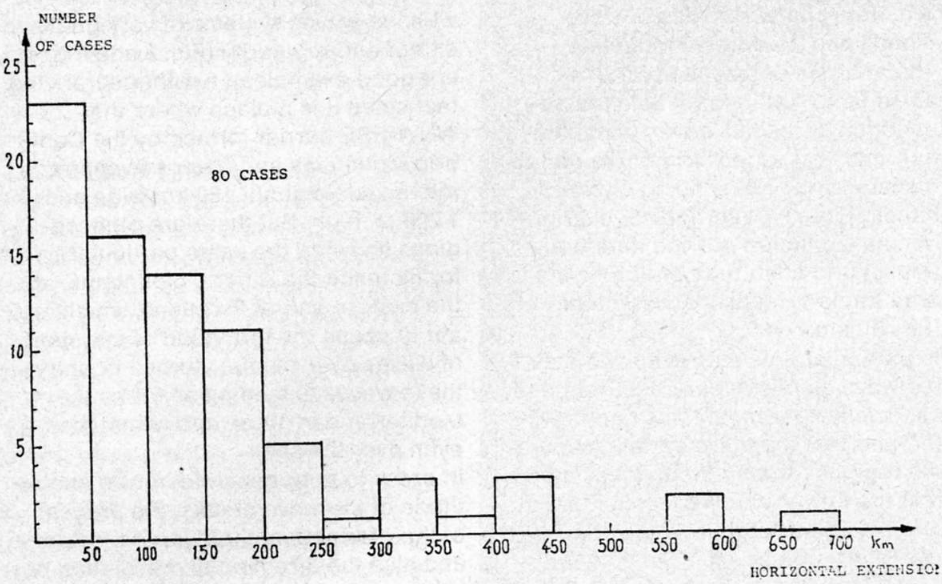


Fig. 6. Distribution of lee-ware cloud patterns as a function of their horizontal extension (system length).

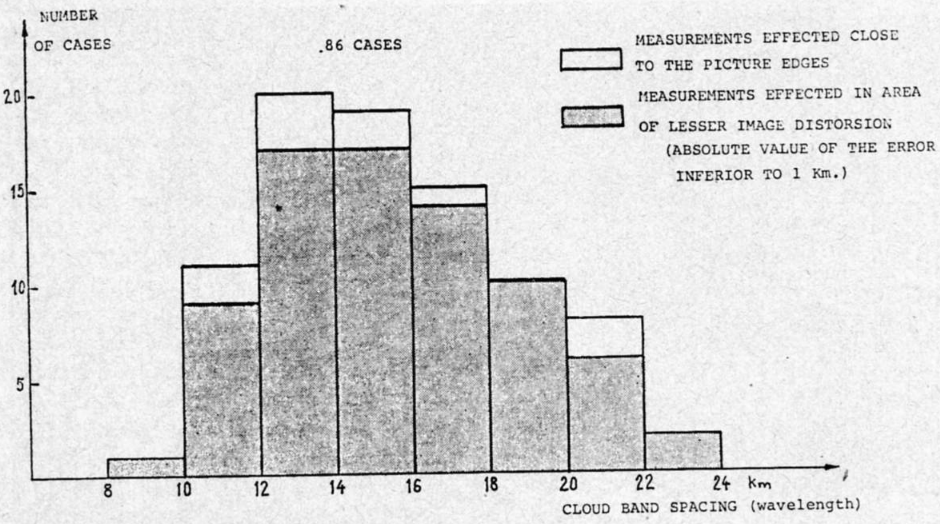


Fig. 7. Distribution of lee-wave cloud patterns as a function of their wavelength as measured on pictures.

associated motions, we made use of observations and measurements effected aboard aeroplanes and gliders. Cloud bands appearing on satellite pictures generally consist of stratocumulus (base 1 000 to 1 500 m. high, top rarely exceeding 4 000 m.) eventually surmounted by lenticular altocumulus (culminating at 6 000 to 7 000 m.). Although the banded stratocumulus can be likened to conventional rotor clouds, they are not always associated with such rotors in the atmospheric layers close to the ground: they often originate from the modulation of an initially continuous stratocumulus by higher wave motions, and sometimes apparently result from a convective cumulus formation just below the wave crests.

Turbulence encountered by areoplanes or gliders was essentially located in the lower layers or quite close to the stratocumulus, and very variable from day to day.

An attempt to estimate the vertical extent of wave motions was made on the basis of club reports, giving the maximum altitudes reached by gliders. We found such data for 22 cases of cloud bands, and the corresponding histogram (Fig. 9) strongly suggests that the associated wave motions are mostly located in the lower and middle troposphere, except in a few cases. This result is confirmed by the measurement flights effected in 1966, 1969 and 1970: in 31 wave situations, the gliders could exceed 6 000 m. in 10 cases, and 8 000 m. in only 4 cases. These flights also permitted an estimation of the settling time of a stationary wave system (a few minutes) and its duration (several hours).

3.2. Factors determining the occurrence and characteristics of wave clouds

We shall first consider the meteorological factors (synoptic situation, wind

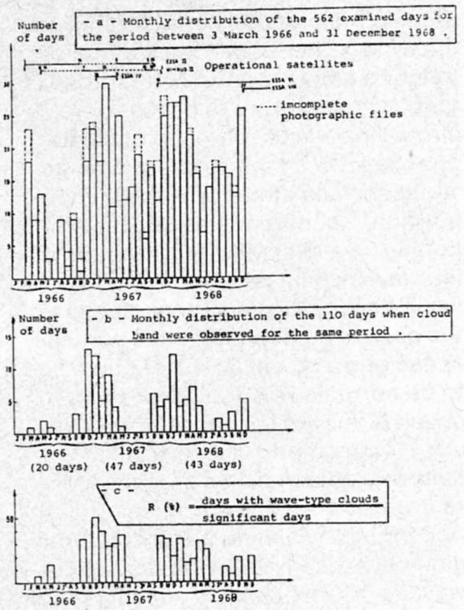


Fig. 8. Seasonal variations of lee-wave cloud pattern occurrence: Although our research in C.E.M.S. photographic files was not systematic (Fig. 8a), the monthly distribution of days with cases of wave-type clouds (Fig. 8b) points to strong seasonal variations, still persisting in the ratio between the number of days with wave-type clouds and number of days when pictures could be effectively examined (significant days).

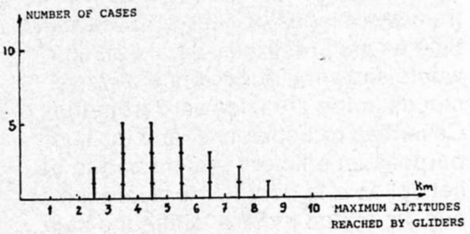


Fig. 9. Distribution of cloud bands cases in function of maximum altitudes reached by gliders.

TABLE 1

MOUNTAIN AREAS (1000m altitudes	180 cases	74,7%
HILLY AREAS (from 200 to 1000m)	46 cases	19,1%
FLAT LAND AREAS (200m altitude)	6 cases	2,5%
OVER THE SEA (not under leeward conditions)	9 cases	3,7%

Distribution of cloud bands in relation to mean altitude of underlying area.

TABLE 2

Type of prevailing conditions	Number of cases	Percentage
- Northerly quasi-meridian type	14	21%
- Southerly quasi-meridian type	12	18%
- Westerly quasi-zonal type	9	14%
- Intermediate type	24	37%
- Special cases	7	10%

Distribution of lee wave cloud cases in function of the different favourable synoptic conditions.

distribution, fronts and air-masses, vertical distribution of static stability), then the geographical ones.

3.2.1. Relation to synoptic weather situation

It is quite obvious, on satellite pictures, that some synoptic situations are particularly favourable to the occurrence of lee-wave clouds. Furthermore, every time such a situation is observed on the surveyed area, the geographic location and general aspect of the systems of wave clouds are strikingly similar: this is the case for the first three types described below, corresponding to well-defined synoptic regimes for Western Europe (a synoptic regime is a quasi-stationary synoptic situation). More generally, we were led to distinguish four types of favourable conditions according to which the classification of table 2 was established: in 66 cases of lee-waves which were studied, only 7 could not be placed in one of the corresponding four categories. The definitions of the types are based on the situation at the 500 mb level, as follows:

a) Northerly quasi-meridian type
(cf. Fig. 10). At 500 mb the mean wind direction is between NNW and N, and usually there is an anticyclone over the eastern Atlantic, centered not far from the coasts of France or Portugal. The cloud bands are generally observed over the British Isles, Lower Languedoc and eastern North Africa. This situation can occur at any season, during 2 to 5 consecutive days (Fig. 2, 3 and 4).

b) Southerly quasi-meridian type
(cf. Fig. 11). At 500 mb the mean wind direction is between S and SW, and usually there is a trough or cyclonic cell on the near eastern Atlantic. The location of cloud bands depends on the mean longitude of the zone of strongest winds: sometimes over Portugal and western Spain, sometimes over central Spain, northern Pyrenees, French Central Plateau and Germany, sometimes also over the southern Alps. This situation is observed mostly in February and October–November and can last from 3 to 4 consecutive days.

c) Westerly quasi-zonal type
(cf. Fig. 12). At 500 mb the mean wind direction is between WSW and WNW. The location of cloud bands now depends on the mean latitude of the zone of strongest winds: either over northern Spain and French Central Plateau or over the Vosges (in France) and Black Forest (in Germany). This situation is observed mostly in January, less frequently in December or February, and

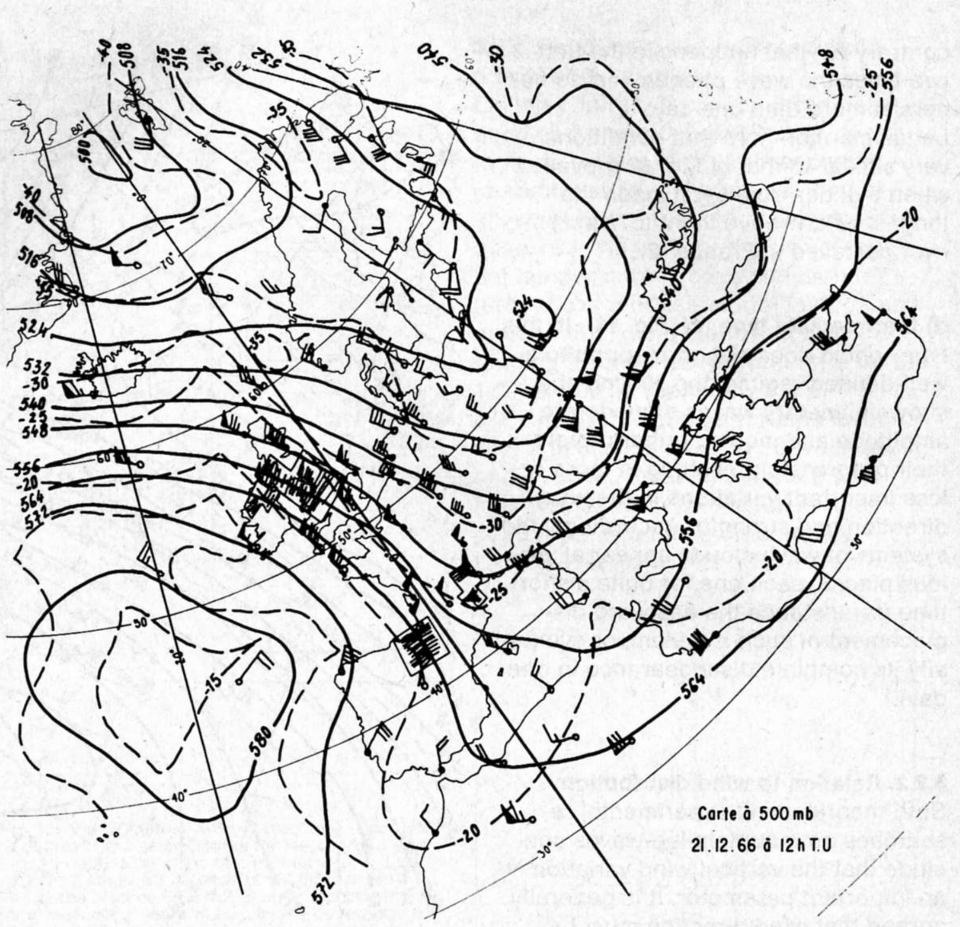


Fig. 10. Chart at 500 mb on 21 December 1966 at 12H G.M.T.

Fig. 11. Chart at 500 mb on 21 October 1967 at 12H G.M.T.

contrary to what happens in the first two types the wave phenomena do not persist more than one day.
Let us mention here that conditions very similar to that of Fig. 12 prevailed when a glider from Lyon made the longest return wave flight (570 km.) ever achieved in France (2).

d) Intermediate type (cf. Fig. 13). In this type, which does not correspond to a well-defined regime, the 500 mb chart shows planetary waves of moderate amplitude and moving rather rapidly, their progression resulting in more or less important variations in the wind direction and strength. Accordingly the systems of wave clouds appear at various places, each one for quite a short time (for instance the eastward displacement of such a system, or eventually its complete disappearance in one day).

3.2.2. Relation to wind distribution

Both theorical and experimental researches on mountain lee-waves conclude that the vertical wind variation is an important parameter. It is generally agreed that wind direction must be nearly perpendicular to the mountain range and that its speed must increase with height, or at least remain constant, in a layer extending from the crest level to the upper troposphere.
Observations also suggest that waves can occur only if the wind speed at a given level (the crest level in most of cases) is not smaller than a certain «threshold speed», ranging from 8 to 13 m/s and increasing with the mountain height.
Furthermore several authors (CORBY, 1957; ALAKA, 1958; GEORGII, 1967), established that the wavelength must increase linearly with the average wind speed in the troposphere, and this result was used in an attempt to deduce this average speed from the spacing of the cloud bands measured on satellite pictures (FRITZ, 1965).
We compared these various results with wind data concerning cloud band cases, and our conclusions were as follows:
a. As already mentioned in the cases of synoptic regimes, the systems of cloud waves are, as a rule, located along the zones of strongest winds at 500 mb.
b. Band direction seems closely related to that of the wind at altitude, more so than to the wind direction at lower levels (Fig. 14 and 15). More precisely, the band direction is very nearly perpendicular to the air flow above a certain altitude depending on the mountain range: 1 500 to 2 000 m. in the case of «La Montagne Noire» or Espinouse, 2 500 to 3 000 m. in the Pyrenees.

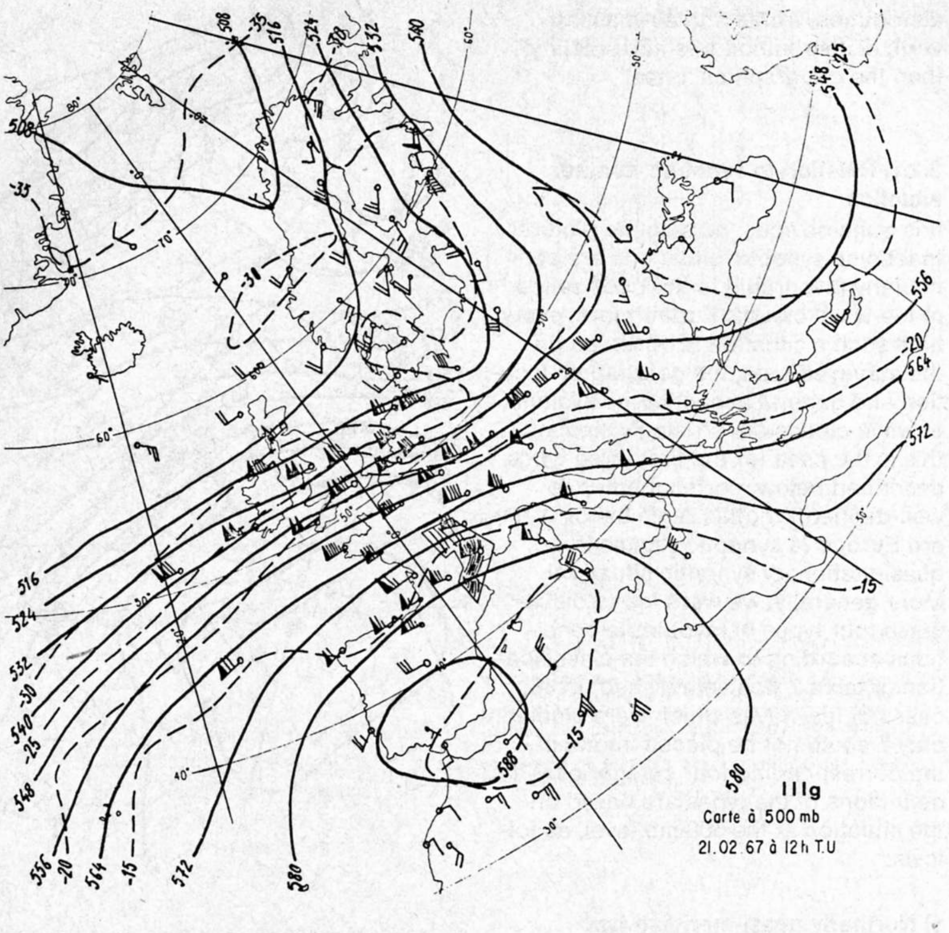


Fig. 12. Chart at 500 mb on 21 February 1967 at 12H G.M.T.

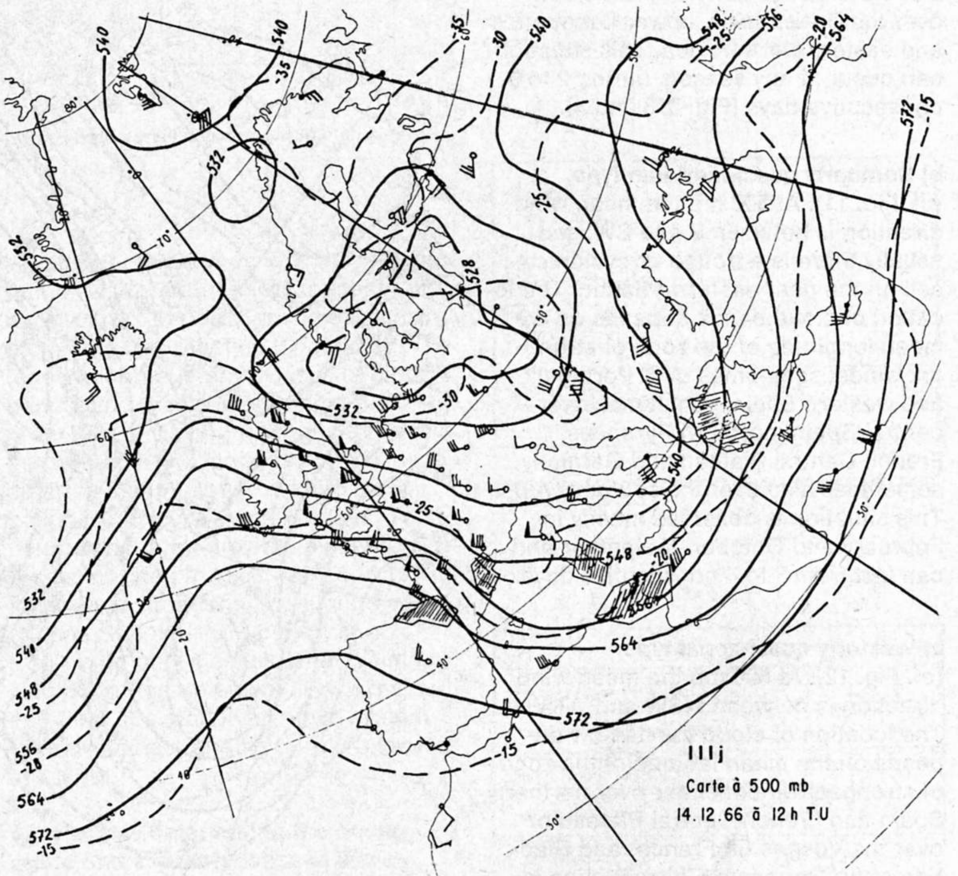


Fig. 13. Chart at 500 mb on 14 December 1966 at 12H G.M.T.

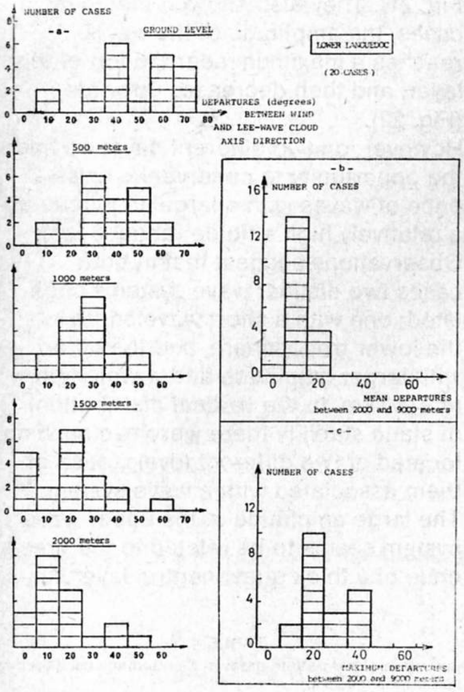


Fig. 14. Departures between wind direction and lee wave cloud axis direction at different level. We have compared the wind direction at different level with the axis direction of the lee-wave cloud patterns (direction perpendicular to the cloud bands). For the Lower Languedoc area (Fig. 14a), the histogram shows a maximum for departures whose values decrease when increasing altitude. At 2 000 metres the maximum corresponds to values of ten degrees. Above this level (Fig. 14b) the mean departure is most generally of ten degrees and always inferior to thirty degrees. If we examine the maximum value of the deviation between 2 000 and

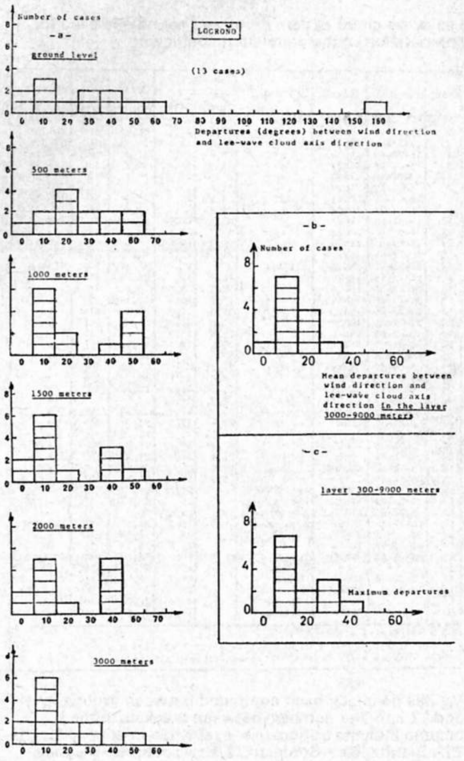


Fig. 15. 9 000 metres, we can see that it can attain 40 degrees. The same figures for the Logroño area (Fig. 15a and 15b) show that the departures can frequently attain 40 degrees at 2 000 metres. It is only at the altitude of 3 000 metres that the histogram presents a sharp maximum for departures of 10 degrees, being then comparable to the histogram at 2 000 metres for the Lower Languedoc area.
Between 3 000 and 9 000 metres the mean and the maximum departures are the same as those observed for the Lower Languedoc.

c. From the minimal speeds at such levels we can deduce the threshold speed for each mountain, namely 6 m/s in Lower Languedoc and 10 m/s in the Logroño region (Fig. 16).

d. The wind component perpendicular to cloud bands usually increases with height, but this increase is far from regular, and moreover it can change substantially from day to day.

e. There is no clear relationship between the vertical profile of this wind component and the vertical or horizontal extent of lee-waves (Fig. 17 and 18).

f. For 45 cases of wave-type clouds, we measured the cloud-band spacing and computed the average wind speed in the troposphere. The graph of the first of these quantities versus the second (Fig. 19) suggests a positive linear correlation (the wave-length increasing with average wind speed), but with a rather small coefficient: 0.72, against 0.91 as found by CORBY though based on only 26 cases. We also showed that in 50% of the cases we considered, the departure from a linear increase cannot be ascribed, as suggested by FRITZ, to a deviation of the mean static stability β_m (Fig. 20) from its normal value.
In these conditions it seems difficult to deduce the average tropospheric wind-speed from the cloud-band spacing measured on satellite pictures.

3.2.3. Relation to fronts and air-masses

The existence and horizontal extent of lee-wave clouds cannot be related to a specific type of frontal condition (head of warm front, warm sector, etc.; 39 cases studied), nor to the presence of an air-mass limit (33 cases studied), nor even to a particular type of air-mass (12 cases studied).

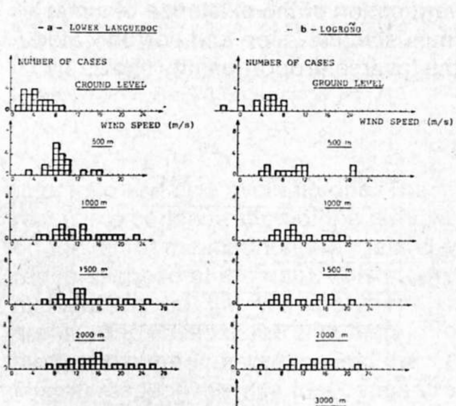


Fig. 16. Wind speed (measured in the direction perpendicular to cloud bands) at different levels.
This figure gives the distribution of wind speed at the same levels as in figures 14 and 15. These histograms indicate a mean increase of wind speed with altitude. The maximum of wind speed at these different levels also increases with height. Its value at the 2 000 m level for the Lower Languedoc area and at the 3 000 m level for the Logroño region can be considered as the «Threshold speed» for each of this two regions.

3.2.4. Relation to the vertical distribution of static stability

On the contrary there is a large influence of the vertical distribution of static stability upon the occurrence and characteristics of lee-waves. First of all, everywhere that cloud waves are observed, the vertical profiles of potential temperature show a common feature: above a quasi-neutral layer (small or even negligible static stability) extending from almost ground level up to 1 000–4 000 m. (generally 1 000–2 000 m.), there is a very stable layer with a thickness ranging between 500 and 4 000 m., itself surmounted by a less stable layer. This result is to be compared with those obtained by LARSSON (1954): this author also noted that soundings at Frösom (Sweden), when wave-type clouds are visible from the ground, revealed a strongly stable layer between 1 000 and 3 000 m., with less stable air above.

Secondly, if the thickness of this highly stable layer is plotted against the horizontal extent of the lee-waves (Fig. 21), an obvious correlation appears: as a first approximation, we can say that this horizontal extent is inversely proportional to the thickness of the layer. Therefore the concentration of static stability in a thin layer is favourable to the horizontal extension of the lee-waves produced by a mountain range, so that this layer appears to behave as

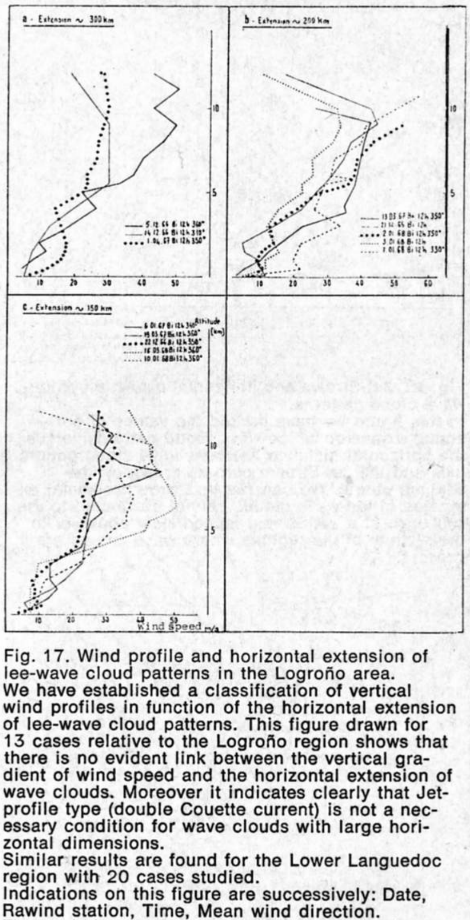


Fig. 17. Wind profile and horizontal extension of lee-wave cloud patterns in the Logroño area.
We have established a classification of vertical wind profiles in function of the horizontal extension of lee-wave cloud patterns. This figure drawn for 13 cases relative to the Logroño region shows that there is no evident link between the vertical gradient of wind speed and the horizontal extension of wave clouds. Moreover it indicates clearly that Jet-profile type (double Couette current) is not a necessary condition for wave clouds with large horizontal dimensions.
Similar results are found for the Lower Languedoc region with 20 cases studied.
Indications on this figure are successively: Date, Rawind station, Time, Mean wind direction.
The rawind stations are Biarritz (Bi) and Bordeaux (Bx).

a wave guide where most of the energy of the waves is «trapped», and propagates mostly horizontally, downstream from the mountain range. Obviously the situation is very similar to that of the classical gravity waves observed for instance at the free surface of a motionless sheet of water surmounted by quiet air, or at the interface between two motionless liquids of different densities: in both cases we are dealing with «surface waves» controlled by a static stability which is infinitely concentrated at the free surface or interface, and if viscosity can be neglected there is no downstream damping of the waves, their amplitude usually reaching a maximum at the free surface or interface, and rapidly decreasing upwards. Actually several of our field experiments (in 1969–1970) were conducted in order to obtain information on the vertical variation of the amplitude of the waves with the vertical distribution of static stability. The recorded measurements made possible the effective verification of the existence of a maximum stability layer, and corroborated the inverse proportionality shown by Fig. 21). They also showed that in most cases, the amplitude of the waves reaches a maximum near the top of this layer, and then decreases upwards (Fig. 22).

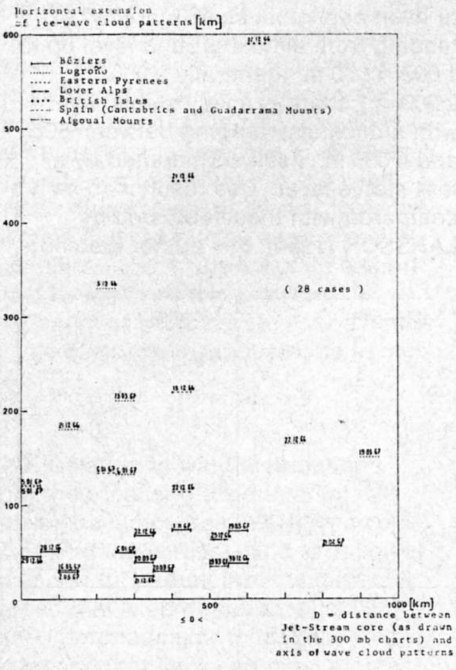


Fig. 18. Jet-Stream and horizontal extension of lee-wave cloud patterns.
In this figure we have plotted the values of horizontal extension of lee-wave cloud patterns versus the horizontal distance between wave cloud pattern axis and the Jet-Stream core as drawn on the 300 mb charts. We can see that wide horizontal extension of lee-wave clouds cannot be related to the presence of a Jet-Stream immediately above or in the vicinity of the regions where wave clouds are present.

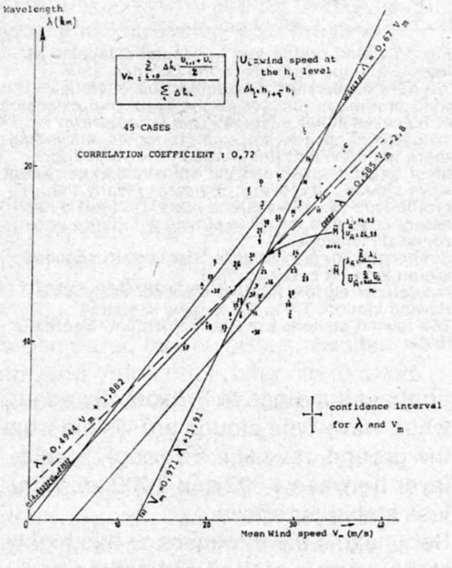


Fig. 19. Correlation between measured wavelengths (λ) and mean wind speed in the troposphere (V_m).
Labelled points correspond to the cases indicated in Table 3
V_m has been calculated with the formula written on the top of the figure. In this formula, U_{i+1} and U_i are the wind speed at the levels h_{i+1} and h_i, and $\Delta h_i = h_{i+1} - h_i$.
The continuous lines $\lambda = 0.5272\ V_m + 0.7532$ (1) and $V_m = 0.971\ \lambda + 11.91$ (2), are the regression lines calculated with the data of Table 3. The product of the slopes of these lines gives the correlation coefficient: 0.72. Here only the line No 1 is to be compared with Corby's and Georgii's lines.
The discontinuous line $= 0.4944\ V_m + 1.8882$ has been calculated recently from the same data but by means of an electronic computer. The correlation coefficient then found is: 0.67.

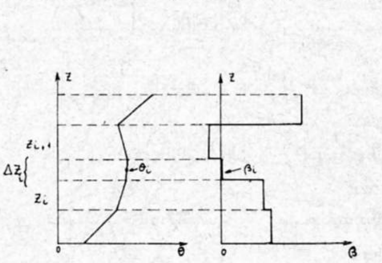
TABLE 3

Lee-wave cloud pattern cases and soundings used for computation of the correlation coefficient.

CASES	DATE	photo TIME	REGION	mean wind speed [m/s]	λ [km]	V_m [m/s] (normal component)	Wind direction [degrees]	Soundings used
1	5-12-66	11h19	Pamplona	33,3	18,3	32,55	360	Bi-12h
2	13-03-67	10h35	"	36,6	11,9	29,48	350	Bx-12h
3	14-12-66	11h40	"	22,8	11,4	22,53	310	Bi-12h
4	16-03-68	10h38	"	33,8	18,2	32,4	360	Bi-12h
5	3-01-68	10h37	"	23,7	14,5	20,6	340	Bi-12h
6	10-01-68	11h08	"	29,3	15	28,1	360	"
7	6-01-67	11h20	"	25,6	13,2	25,3	340	"
8	19-03-67	10h19	"	24,2	11,8	23,7	360	Bx-12h
9	1-04-67	10h26	"	25,8	16,1	25,8*	350	Bi-12h
10	2-01-68	9h44	"	29,1	16,7	26,4 (9km)	350	"
11	7-01-68	10h23	"	33	17,8	32,5 (10km)	330	"
12	21-12-66	11h22	"	25,9	11,9	24,9	360	"
13	22-12-66	10h49	"	21,96	10,75	21,68	350	"
14	14-12-66	11h40	Béziers		20,4	31,5 ([illegible])	330	TB-12h
15	21-12-66	11h18	"	26,3	12	23,1 ([illegible])	330	"
16	22-12-66	10h52	"	28,6	13,5	26,6	340	"
17	24-12-66	11h29	"	18,3	10	17,3 ([illegible])	330	"
18	28-12-66	10h58	"	31,3	12,5	29,2	330	"
19	29-12-66	10h27	"	22,9	11,2	19,85	300	"
20	30-12-66	11h41	"	29,8	12,7	29,3	320	"
21	6-01-67	11h17	"	26,1	16,2	25,8	340	"
22	21-02-67	10h09	"	30,5	14,4	29,9	290	"
23	2-03-67	9h49	"	31,35	14	30,97	300	"
24	18-03-67	9h47	"	34,4	15	30	330	"
25	19-03-67	10h19	"	27,64	14,4	26,2	340	"
26	20-03-67	10h54	"	25,4	14,3	23,15	360	"
27	6-04-67	9h35	"	25,4	15,7	24,74	310	"
28	1-11-67	11h18	"	24,4	12,3	23,8	310	"
29	29-11-67	9h59	"	21,31	13,7	20,19	320	"
30	3-01-68	10h37	"	27,2	10,7	25,1	340	"
31	4-01-68	9h36	"	27,1	14,8	24,9	340	"
32	5-01-68	10h30	"	21,2	13	20,43	320	"
33	25-12-68	11h09	"	29,6	17	27,9	320	"
A'	13-12-66	12h13	Spain (NW)		13,2	19,3** ([illegible])	320	Ma-12h
D	5-01-67	11h51	Guadarrama		19	25,9*** ([illegible])		LC-12h
D'	5-01-67	11h51	Cantabrics		12,5	25,9		"
E	22-12-66	10h52	British Isles		18,5	24,5*	320	Alder-12h
E'	" "	"	-		12	24,5*	310	"
G	21-12-66	11h25	"		21	35,5*	330	"
I	14-12-66	9h58	Gafsa		17,8	30,2*	320	Gafsa-12h
J	" "	9h56	Sardinia		17,7	26,05*	310	Ajaccio-12h
K	3-01-68	10h40	Ireland		19,3	27,9 ([illegible])	330	Val.-12h
L	19-03-67	10h19	Valence (Fr)		22	30,97	360	Lyon-12h
M	" "	"	Aigoual		17,3	29,71	360	Ni-12h
N	20-03-67	10h54	Aigoual		19,2	30,6	360	"

* Interpolated from charts
** The Madrid sounding at 12h G.M.T. stopped at 7200 m .
*** La Corogne would be preferable but stopped at 4200 m .

V_m has generally been computed between ground level and 12 km. The numbers between brackets in the V_m column indicate tropopause level when inferior to 12 km
Bi = Biarritz, Bx = Bordeaux, T. B. = Toulouse-Blagnac, Ma = Madrid, Val = Valentia, Ni = Nîmes, Al = Aldergrove, L. C. = La Corogne.



In a classical manner , the static stability β is defined by :

$$\beta = \frac{d}{dz}\left[\mathrm{Log}\,\theta\right]$$

where θ is the potential temperature and $\frac{d}{dz}$ the partial derivative with respect to the altitude z .

If we suppose that θ_i is the mean potential temperature of an air layer comprised between levels z_i and $z_{i+1} = z_i + \Delta z_i$ then the static stability of this layer is given by :

$$\beta_i = \frac{1}{\theta_i} \frac{(\Delta\theta)_i}{\Delta z_i} \qquad \text{(see figure 25)}$$

Then our definition of β_m is :

$$\beta_m = \frac{\sum_i \Delta z_i\, \beta_i}{\sum_i \Delta z_i} = \frac{\sum_i \frac{(\Delta\theta)_i}{\theta_i}}{\sum_i \Delta z_i}$$

Fig. 20.

However, on two different days, we had the opportunity to observe the existence of waves with a large amplitude at a relatively high altitude (about 8 km). Observations suggest that in both cases two distinct wave systems coexisted: one with a short wavelength in the lower troposphere, and the other with larger amplitude and wavelength at 7–10 km. In the vertical distribution of static stability there were two maxima located at two different levels, each of them associated with a wave system. The large amplitude of the upper wave system seems to be related to the presence of a thick quasi-neutral layer surmounting the second maximum of static stability. Thus in this quasi-neutral layer, wave motions associated with the second maximum of stability could reach a very large amplitude.

TABLE 4

Lee-wave cloud pattern cases and soundings used for computation of β_m.

DATE	CASES	LOCATION	SOUNDINGS	β_m	λ
V_m=20 m/s					
29-12-66	19	Béziers	Nimes 12h	$1,21.10^{-5}$	11,2 km
5-01-68	32	"	"	"	13 km
13-12-66	A'	Spain (NW)	La Corogne 12h	$1,14.10^{-5}$	13,2 km
V_m=25 m/s					
6-01-67	7	Logroño	Madrid 12h	$1,49.10^{-5}$	13,2 km
21-12-66	12	"	Bordeaux 12h	$1,37.10^{-5}$	11,9 km
4-01-68	31	Béziers	Nimes 12h	$1,29.10^{-5}$	14,8 km
6-04-67	27	"	Bordeaux 00h	$1,39.10^{-5}$	12,7 km
3-01-68	30	"	Nimes 12h	$1,24.10^{-5}$	10,7 km
V_m=26 m/s					
22-12-66	16	Béziers	Nimes 12h	$1,39.10^{-5}$	13,5 km
19-03-67	25	"	"	$1,37.10^{-5}$	14,4 km
1-04-67	9	Logroño	Madrid 12h	$1,03.10^{-5}$	16,1 km
6-01-67	21	Béziers	Nimes 12h	$1,69.10^{-5}$	16,2 km
2-01-68	10	Logroño	Madrid 12h	[illegible]	16,7 km
			Bordeaux 00h	$1,24.10^{-5}$	
5-01-67	D'	Cantabrics	La corogne 12h	$1,43.10^{-5}$	19 km
	D	Guadarrama	Madrid 12h	$1,29.10^{-5}$	12,5 km
V_m=30 m/s					
13-03-67	2	Logroño	Madrid 12h	$1,24.10^{-5}$	11,9 km
28-12-66	18	Béziers	Nimes 12h	$1,35.10^{-5}$	12,5 km
30-12-66	20	"	"	$1,1\ .10^{-5}$	11,7 km
21-02-67	22	"	"	$1,28.10^{-5}$	14,4 km
18-03-67	24	"	"	$1,48.10^{-5}$	15 km
19-03-67	M	Aigoual	"	$1,37.10^{-5}$	17,3 km
20-03-67	N	"	Lyon 12h	$1,29.10^{-5}$	19,2 km
OTHER POINTS					
22-12-66	13	Logroño	Bordeaux 00h	$1,42.10^{-5}$	10,7 km
21-12-66	15	Béziers	Nimes 12h	$1,26.10^{-5}$	12 km
22-12-66	E'	British Isles	Shanwell 12h	$1,18.10^{-5}$	12 km
21-12-66	G	"	"	$1,36.10^{-5}$	21 km
19-03-67	L	Valence (Fr)	Lyon 12h	$1,43.10^{-5}$	22 km

More generally, a favourable factor for the formation of wave motion with a large amplitude at high level could be the existence, between the layer of maximum stability and the tropopause, of a quasi-neutral thick layer.

3.2.5. Geographical factors

The study of geographical distribution of lee-wave cloud patterns points out the existence of preferential geographical areas. Moreover the horizontal extent of these banded clouds is generally depending on the site considered. Therefore, it was legitimate to study the possible influence of regional geomorphology, on the formation of banded clouds as well as on their horizontal extent.

It is interesting to correlate the existence of areas particularly favourable to

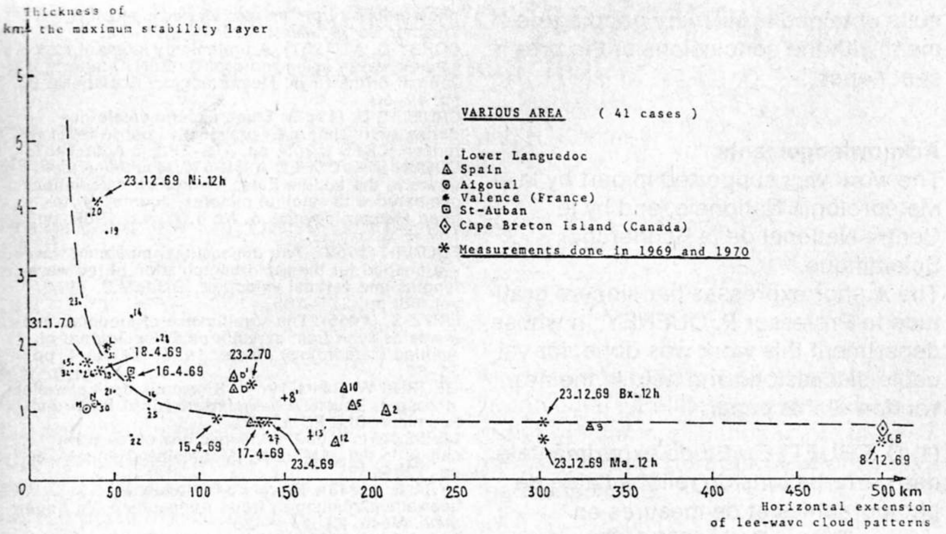


Fig. 21. Influence of thickness of the maximum stability layer on lee-wave cloud pattern horizontal extension.

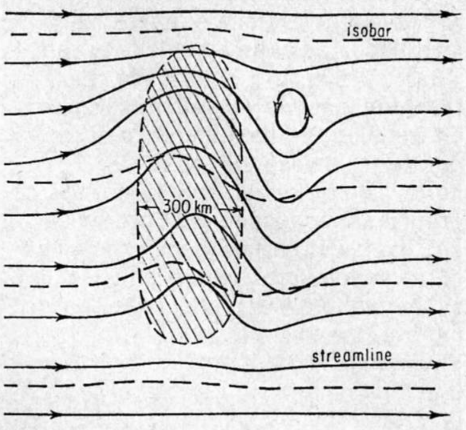


Fig. 23. Synoptic scale orographic peturbation of an uniform wind speed by a mountain range (accrding to P. QUENEY).

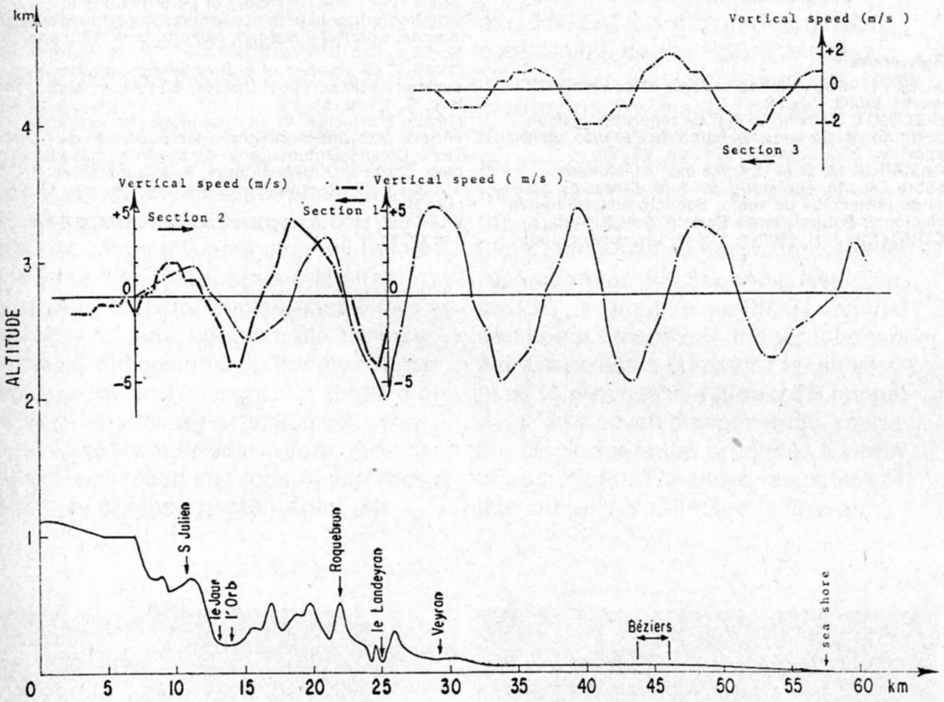


Fig. 22. Vertical component of wind speed in waves produced by Espinouse Mountains (January 16., 1970).
These measurements were taken by means of an aeroplane belonging to the Pézenas Airclub, on January 16., 1970, between 15H06 and 15H47 local time, at mean altitudes of 2 800 m (section land 2) and 4 200 m (section 3). Arrows indicate the direction followed by the plane. Wind blows from left to right of the diagram.
Six waves are visible but there were probably several others over sea where, for safety reasons, the aeroplane did not pursue its measuring mission.
Mean wavelenght is about 10 km. As well at 2 800 m as at 4 200 m. But vertical speed intensity is twice weaker at 4 200 m than at 2 800 m.

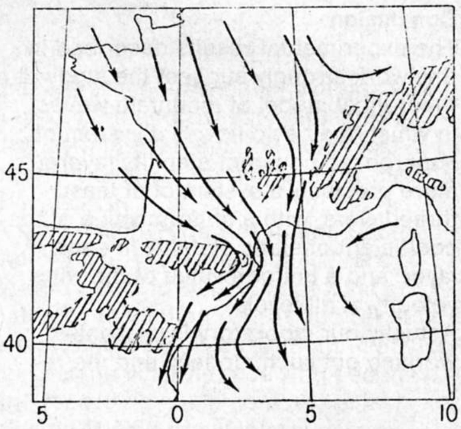


Fig. 24a. Mistral and Tramontane formation according to P. QUENEY.

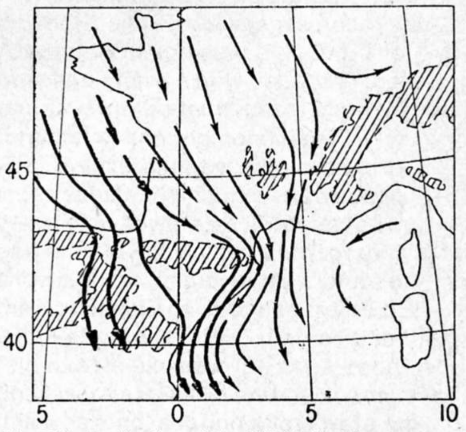


Fig. 24b. Application of the QUENEY's Theory: Concentration of the wind to the East of the Cantabric range.

the occurrence of the phenomenon, with a theory by Professor P. QUENEY on meso-scale orographic perturbations. This theory (P. QUENEY – 1962) indicates that: «with a mountain range the width of which exceeds 100 km, there is a predominant asymetric horizontal deformation of the streamlines associated with their vertical deformation». The Fig. 23 shows a typical aspect of this horizontal deformation at some level of the lower troposphere, in the case of a straight isolated range located in the northern hemisphere and far from the equator. There is an anticyclonic deformation of streamlines and horizontal isobars above the mountain, followed by a cyclonic one. The result is a concentration of the airflow on the left of the mountain range and a reduced speed at the right. This theory explains most of the well-known regional winds associated with high mountains: the Tramontane and the Mistral respectively due to a concentration of a northwesterly wind by the Pyrenees and the Central Plateau (Fig. 24a), and the strong westerlies sometimes observed along the eastern coast of North Africa, due to a similar concentration of a northwesterly wind by the Atlas.

Thus, it can be noted that there is a very good correlation between these areas of wind concentration and areas where lee-wave cloud patterns are frequently observed when the general wind is from NW to N: North Africa, Lower Languedoc, and Eastern Pyrenees and the Logroño area. In this latter case, the air-flow concentration is due to the Cantabric mountains (Fig. 24b).

Lastly we propose an explanation for the formation of large-extent banded clouds over the Upper Ebro Valley under Northerly conditions. Measurements by means of gliders at Huesca (Upper Ebro Valley) show (M. C. CAMARGO, 1954) that, under such conditions there is always a very stable but rather thin layer (temperature-inversion layer), located at an altitude between 1 800–2 000 m. and 2 400–2 600 m.

We think that this very stable layer can be explained by the difference of temperature between the top of the northwesterly wind blowing near the ground surface along the Ebro Valley, and the lower part or the northerly flow of the middle troposphere which is submitted to a foehn effect after passing over the Pyrenees.

The results (§ 3.2.4 and Fig. 21), show that the thin and very stable layer thus created is favourable to the formation of lee-wave cloud patterns with large horizontal dimensions.

Conclusion

The experimental results described in this work strongly suggest the study of a theoretical model of mountain waves in which the basic flow is a system of superposed constant-stability layers: more precisely a system of at least three layers, with a uniform value of the coefficient of static stability in each layer, and a uniform value of the wind velocity at all levels.

Actually our laboratory is presently working out such models, and the results obtained are in very good agreement with the conclusions of the present paper.

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(2) On January 1971 (cf. Aviasport Journal, No 203, April 1971).

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