Experimental study of mountain lee–waves by means of satellite photographs and aircraft measurements

By DENISE CRUETTE, *University of Paris VI, Physique et Dynamique de l'Atmosphère, Tour 14, 4, Place Jussieu, 75230 Paris Cedex 05, France*

(Manuscript received September 26, 1974; in final form February 16, 1976)

ABSTRACT

This paper is a summary of a Ph.D. Thesis[1] which was a systematic study of the influence of various meteorological factors on the occurrence and characteristics of mountain waves, more specifically of lee-waves of great horizontal extent. The data used are, beside classical meteorological informations, that given by satellite pictures completed by quasi-simultaneous measurements from planes 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 to the thickness of this highly stable layer, which thus appears to act as a wave guide where almost all the energy of the mountain perturbation is "trapped", in the same way as ordinary gravity waves are produced and retained at the free surface of a quiet sheet of water (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 light by glider pilots, and interest in them has given rise to many theoretical and experimental studies. However, although our knowledge of lee-waves now goes back almost half a century, the process of their formation is still far from completely elucidated.

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

The great extent of a typical lee-wave was really a new fact, as was the apparently comparable importance of lee-waves produced by mountains very different in scale. But it has 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 constant-altitude atmospheric layer, producing a reflection of the wave motion.

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

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

However the published studies relative to the phenomenon can hardly be considered as conclusive, since they all concerned individual cases, and since 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 gives by balloons, planes and gliders.

[1] D. Cruette: Etude expérimentale des perturbations de relief à l'aide de photographies et de mesures en avion. Thèse, Paris, 1973 (400 pages).

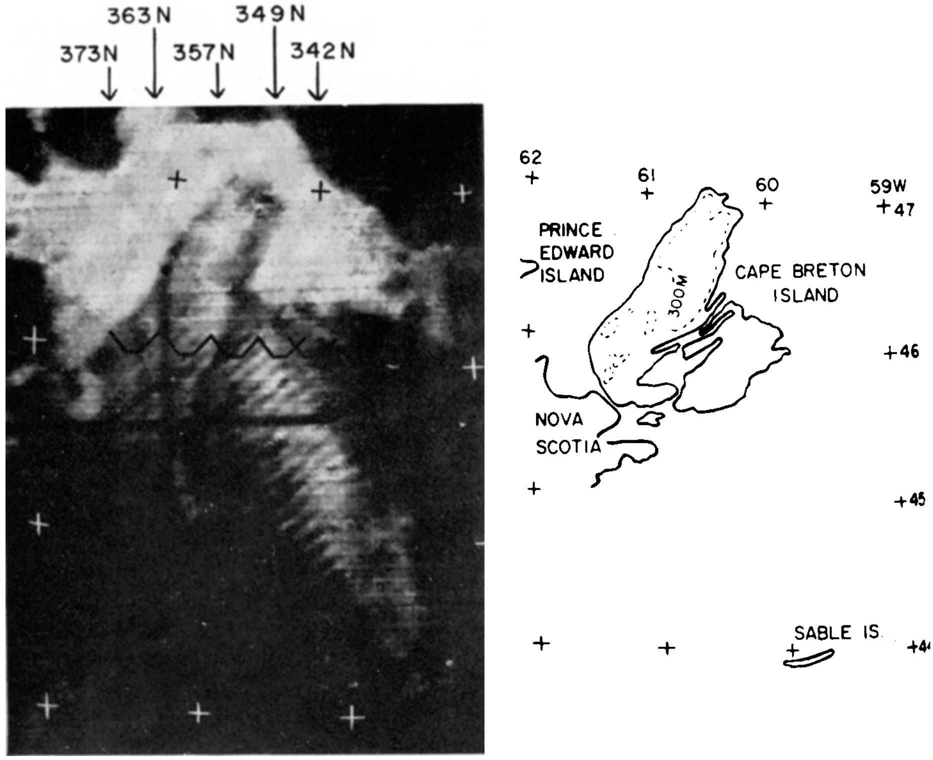

Fig. 1. Lee-wave cloud pattern downwind from Cape Breton Island (Canada). This cloud system extends over 250 km downwind from the island, which culminates at an average altitude of 300 m. Cloud band spacing is 8.3 km (according to J. Conover (1964)).

2. Working methods

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

2.1. *Collection and use of existing documentation*

The 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, private-plane-pilot clubs, and also to french and spanish gliding associations whose members commonly make wave flights.

We were thus able to select the interesting cases and, this inquiry also provided us with very valuable complementary data. We examined satellite pictures for 562 days and found 277 cases to be retained distributed over 110 days and among which 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*

Informations 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 campaigns conducted in the Pyrenees with the french weather services, in February 1966 and November 1967. Each campaign involved substantial means, both in men (some thirty people) and in instrumentation (in particular: 2 airplanes, 3 to 5 gliders, 2

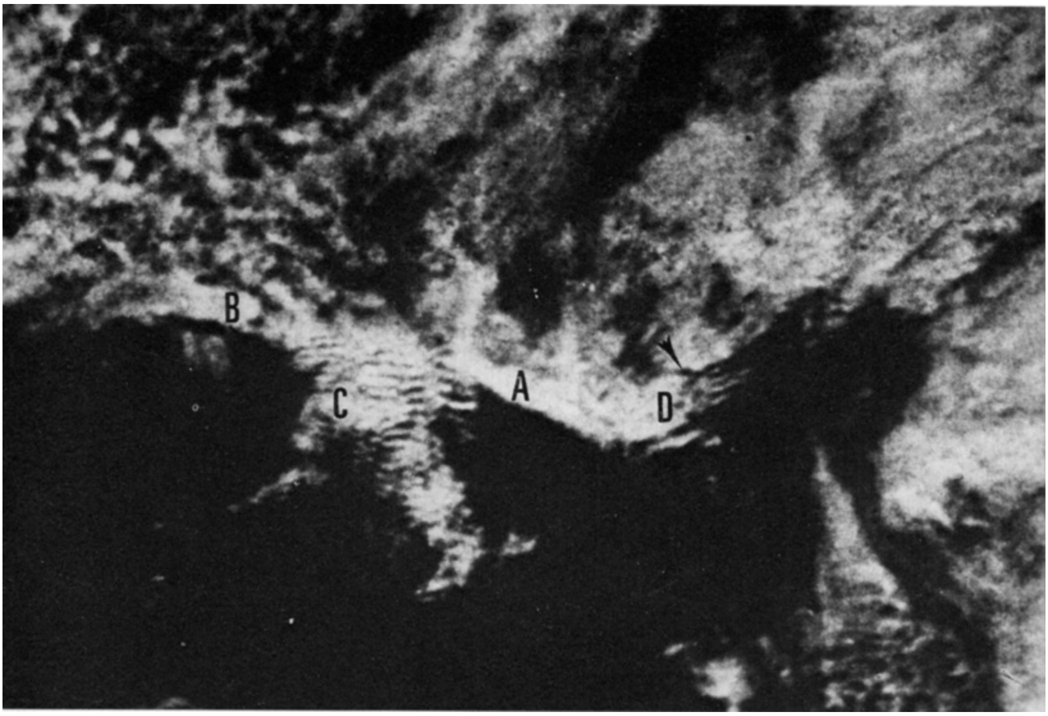

Fig. 2. 23 December 1969 at 11HO9 G.M.T. Nimbus 3, 1837. Photograph by French Weather Service.

radars). The airplanes were used for recording pressure, temperature and humidity (vertical soundings, mainly), and the gliders were intended to developp 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 a small sinking speed (45 to 75 cm/s), they have a very good response to vertical impulses, and owing to the lack of any vibration, they make excellent experimental platforms, especially for measuring air temperature, even 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, which can prove difficult, if not impossible, to launch under strong-wind conditions. 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 planes or ordinary gliders, and actually most of them with gliders. The air temperature and altitude variations were recorded along flights conducted at a constant speed relative 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 of 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 the

Fig. 3. 23 December 1969 around 12H G.M.T. Photograph by J. C. Bisconte (Pezenas).

Legend for photographs 2 and 3: On picture 2, taken on 23 December 1969 at 11HO9 G.M.T. by satellite Nimbus 3, *A* and *B* respectively designate the Pyrenees and the Cantabric Mountains covered with stratocumuli. 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 Airclub. The glider whose approximate position is indicated by the pointed end of the arrow drawn on picture 2, was flying northwards, at an altitude of 4 500 m. The picture was taken eastwards. It clearly shows that cloud bands are stratocumuli; 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.

most likely to appear is the Lower Languedoc area (see § 3.1 hereafter), and moreover it was particularly convenient to our experiments since it is rather 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 planes 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 operate at any time upon a mere telephone call. This system was 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 planes less than one hour after their presence had been announced by Lannion (Figs 2 and 3).

However the satellite pictures revealed rather few cases of lee-wave clouds over the area during these two periods: only 7, against more than 65 days of lee-wave 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 area including Western Europe and North Africa was surveyed by means of satellite pictures (Fig. 5). As previously mentioned, 562 days were examined over a period extending from March 1966 to December 1968.

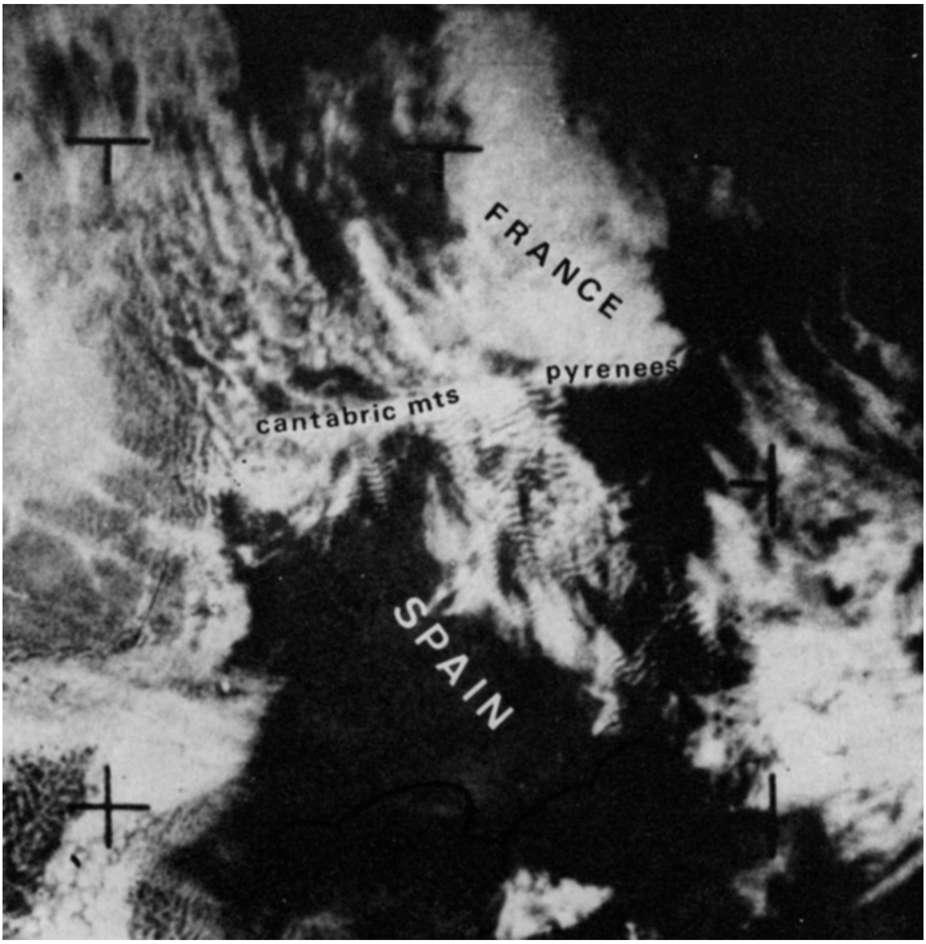

Fig. 4. Lee-wave cloud pattern over Spain. Cloud band spacing of about 18 km. Nimbus 2-3340 8 December 1969 at 10H50 G.M.T. Photograph by Météorologie Nationale.

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. 8) and of altitude of underlying area (Table 1), seasonal variations (Fig. 9), etc ...

In particular, this study showed that lee-wave clouds occur rather frequently, especially near mountains and especially in winter, and most in certain favourable regions. Among these regions, let us mention the Lower Languedoc in France, and the Upper Ebro Valley, in Spain, this latter area being often covered with lee-wave systems of very great extent and regularity (Fig. 2 and Fig. 4 give good examples), a rather surprising fact since it is a place where the WNW-ESE barrier formed by the Cantabric Mountains and Pyrennes, 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 Mounts, at the eastern end of Pyrenees, which are apt to cause the formation of a system of waves over the Gerona flat country. These waves extending as far as the mediterranean shore and sometimes even over the sea.

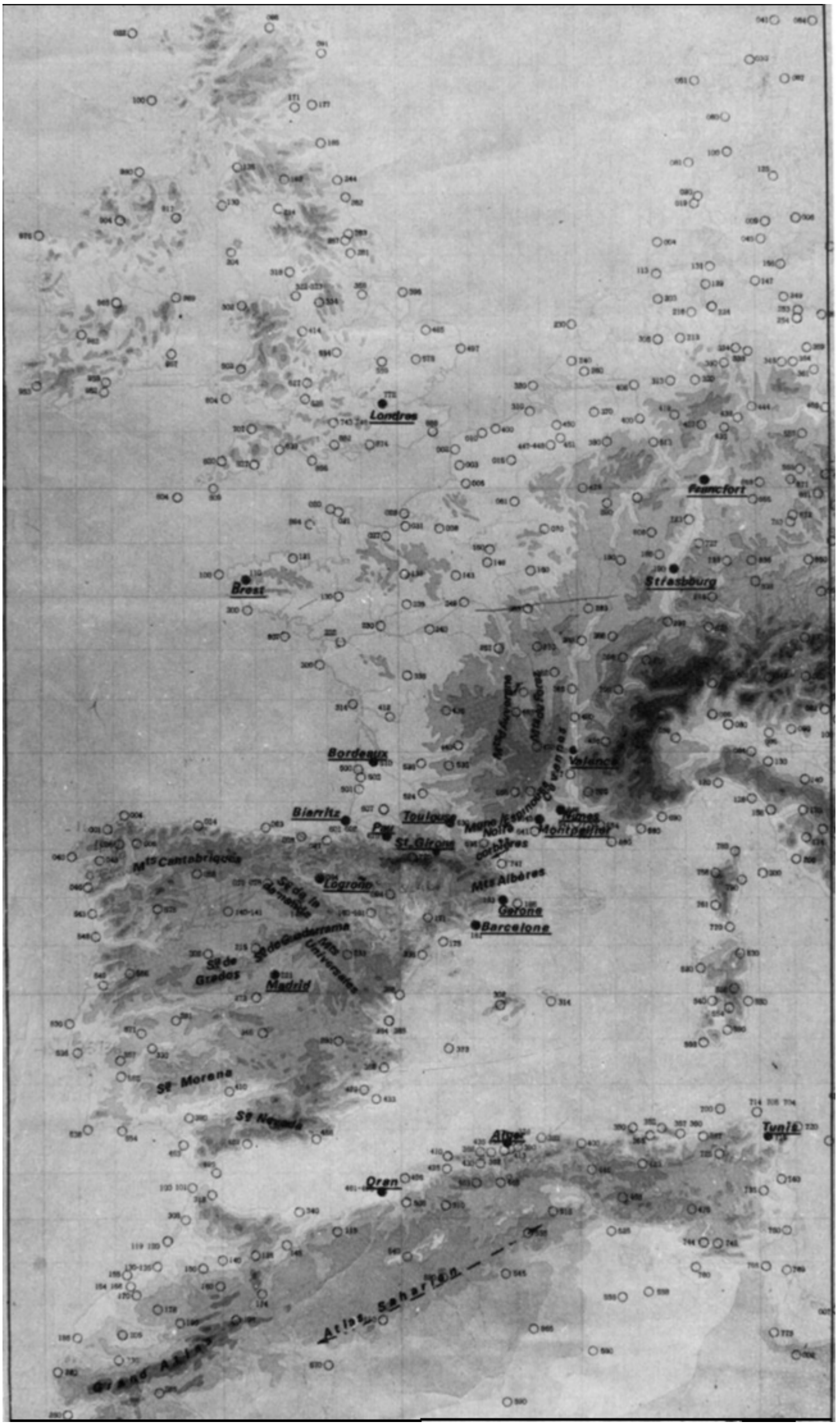

Fig. 5. Surveyed area.

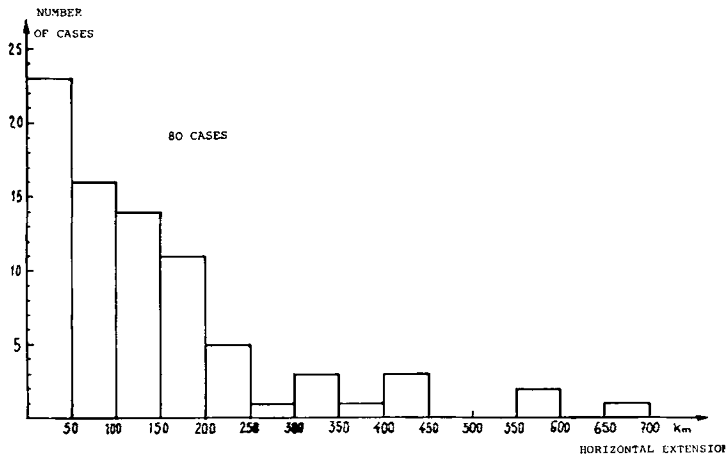

Fig. 6. Distribution of lee-wave cloud patterns as a function of their horizontal extension (system length).

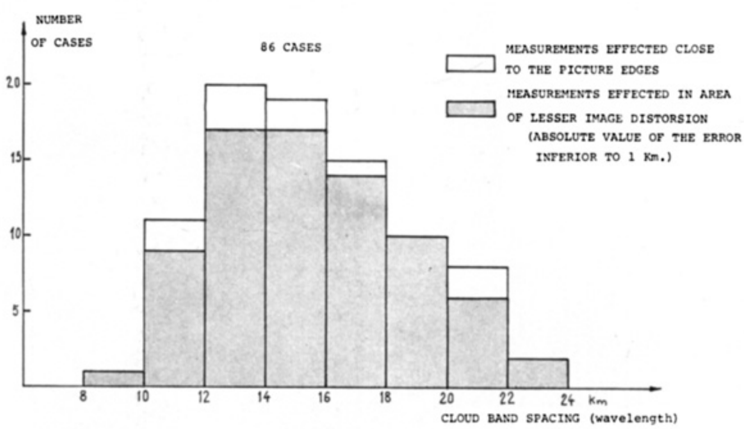

Fig. 7. Distribution of lee-wave cloud patterns as a function of their wavelength as measured on pictures.

In order to specify the nature and altitude of the wave clouds, the process of their formation, their vertical extent, and also the duration and evolution of associated motions, we had to use observations and measurements effected aboard planes and gliders.

Clud bands appearing on satellite pictures generally consist of stratocumuli (base 1 000 to 1 500 m high, top rarely exceeding 4 000 m) eventually surmonted by lenticular altocumuli (culminating at 6 000 to 7 000 m). Although the banded stratocumuli 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 planes or gliders was essentially located in the lower layers or quite close to the stratocumuli, and very variable from day to day.

An attempt to estimate the vertical extent of wave motions was made on the basis of airclub reports, giving the maximal altitudes reached by gliders. We found such data for 22 cases of cloud bands, and the corresponding histogram (Fig. 10) strongly suggests that the associated wave motions are mostly located in the lower and middle troposphere, except in few cases. This result is confirmed by the measuring

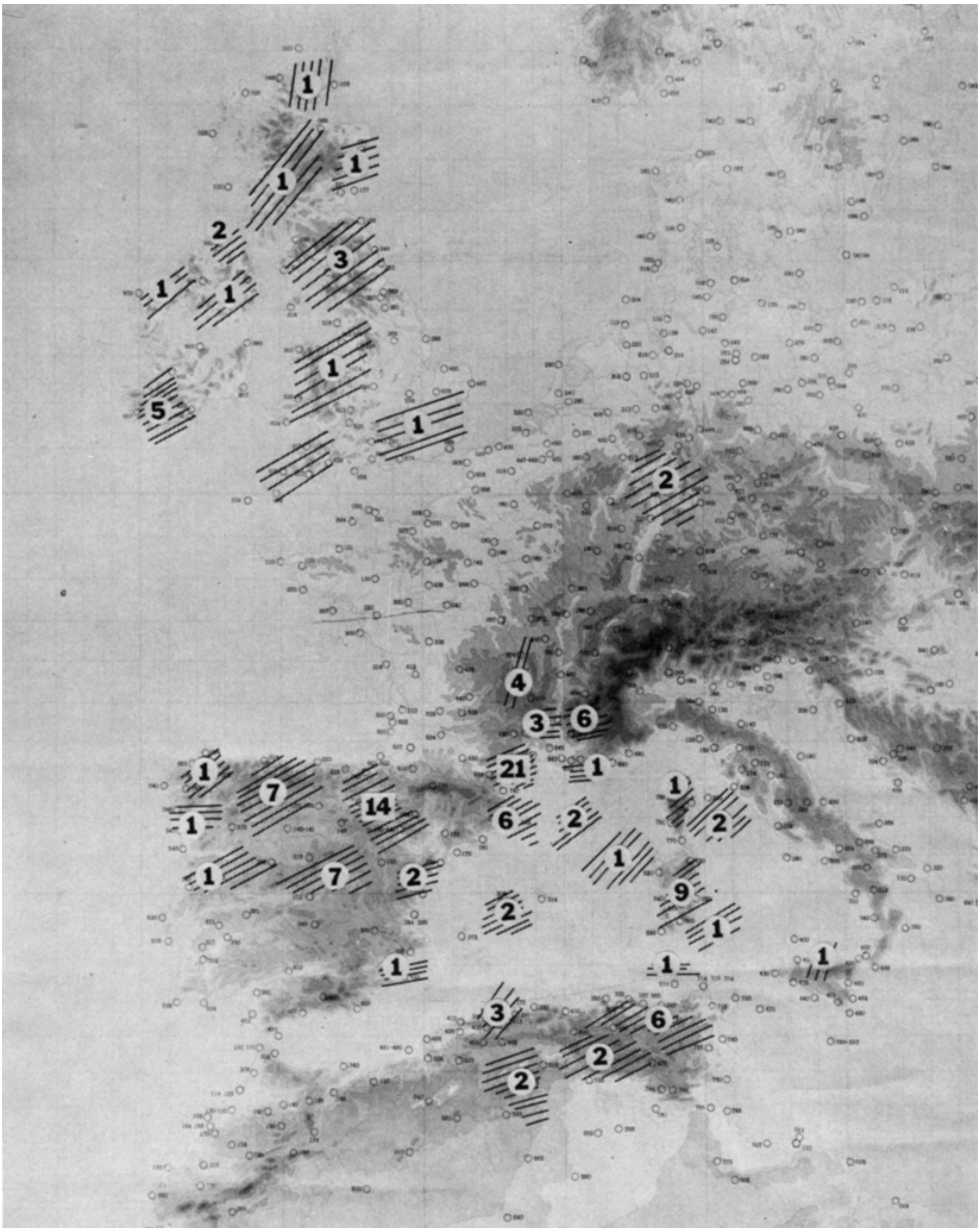

Fig. 8. Northwesterly conditions. Geographical distribution of wave-type clouds with a northwesterly wind. Numbers indicate how many cloud systems were observed in each area for the period between 3 March 1966 and 31 December 1968.

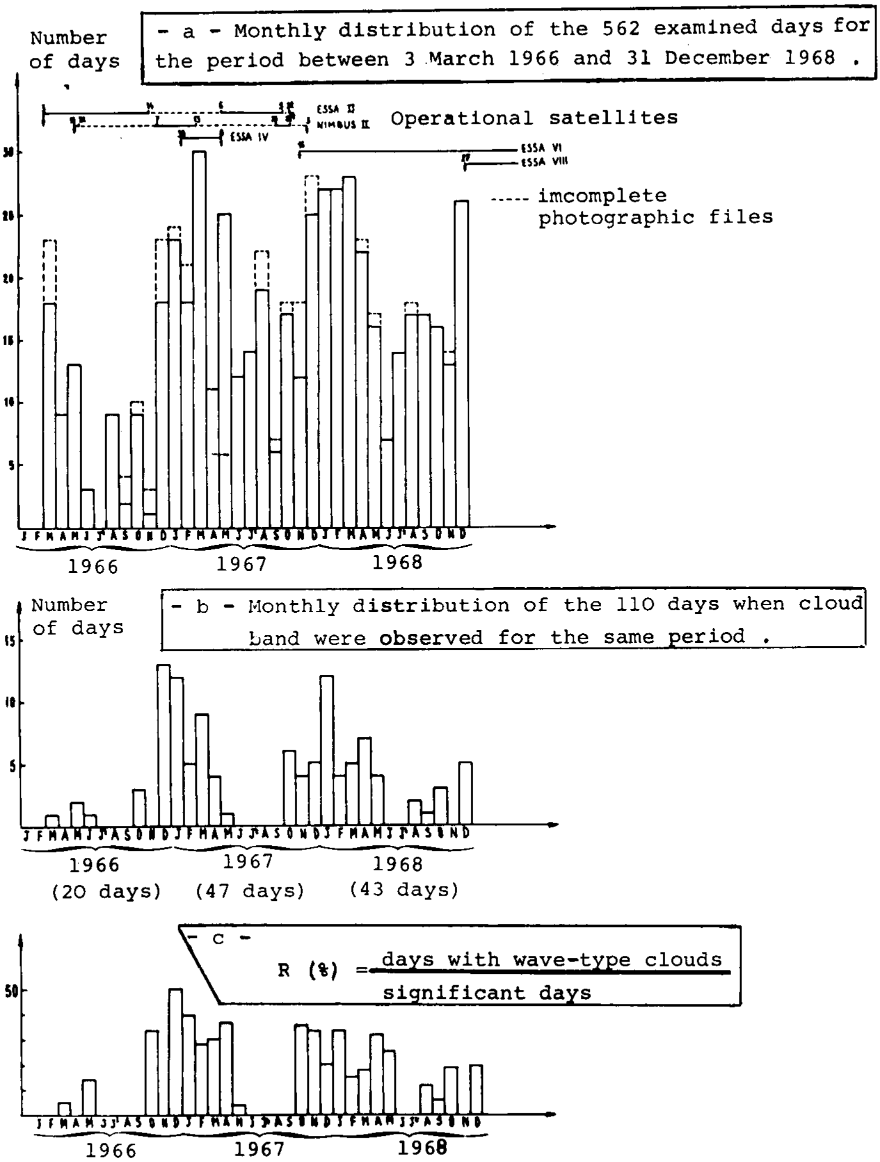

Fig. 9. Seasonal variations of lee-wave cloud pattern occurrence. Although our research in C.E.M.S. photographic files was not systematic (Fig. 9*a*), our study of the monthly distribution of days with cases of wave-type clouds (Fig. 9*b*) indicates strong seasonal variations, still persisting in the ratio between the number of days with wave-type clouds and number of days when pictures could be effectively examined (significant days).

flights effected in 1966, 1969 and 1970: on 31 wave situations, the gliders could overpass 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 distribution, fronts and air-masses, vertical distribution of static stability), then the geographical ones.

Table 1. *Distribution of cloud bands in relation to mean altitude of underlying area*

	No. of cases	%
Mountain areas (1 000 m altitudes)	180	74.7
Hilly areas (from 200 to 1 000 m)	46	19.1
Flat land areas (200 m altitude)	6	2.5
Over the sea (not under leeward conditions)	9	3.7

Table 2. *Distribution of lee wave cloud cases in function of the different favourable synoptic conditions*

Type of prevailing conditions	No. of cases	%
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

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 hereafter, 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: on 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 topography of the 500 mb surface, as follows:

(*a*) *Northerly quasi-meridian type* (cf. Fig. 11). At 500 mb the mean wind direction is between NNW and N, and usually there is an anticyclone on eastern Atlantic, centered not far from the coasts of France or Portugal. The cloud bands are generally observed over British Isles, Lower Languedoc and eastern North Africa. This situation can occur at any season, during 2 to 5 consecutive days (Figs 2, 3 and 4).

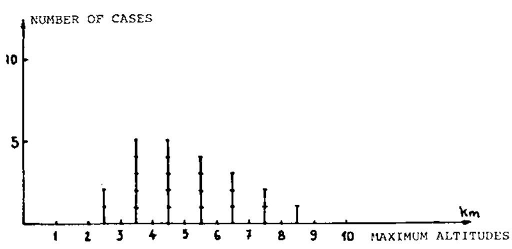

Fig. 10. Distribution of cloud bands cases in function of maximum altitudes reached by gliders.

(*b*) *Southerly quasi-meridian type* (cf. Fig. 12). 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 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. 13). 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 contrarily 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. 13 prevailed when a glider from Lyon made the longest return wave flight (570 km) even achieved in France.[1]

(*d*) *Intermediate type* (cf. Fig. 14). In this type, which does not correspond to a well-defined regime, the 500 mb-map 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 variable places, each one during a rather short time (for instance the east-

[1] On January 1971 (cf. Aviasport Journal, No. 203, April 1971).

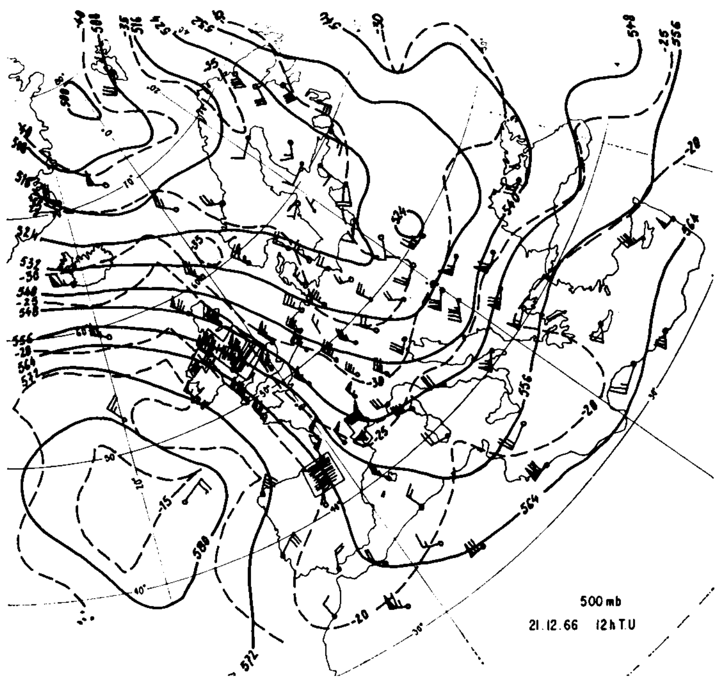

Fig. 11. Chart at 500 mb 22 December 1966 at 12H G.M.T.

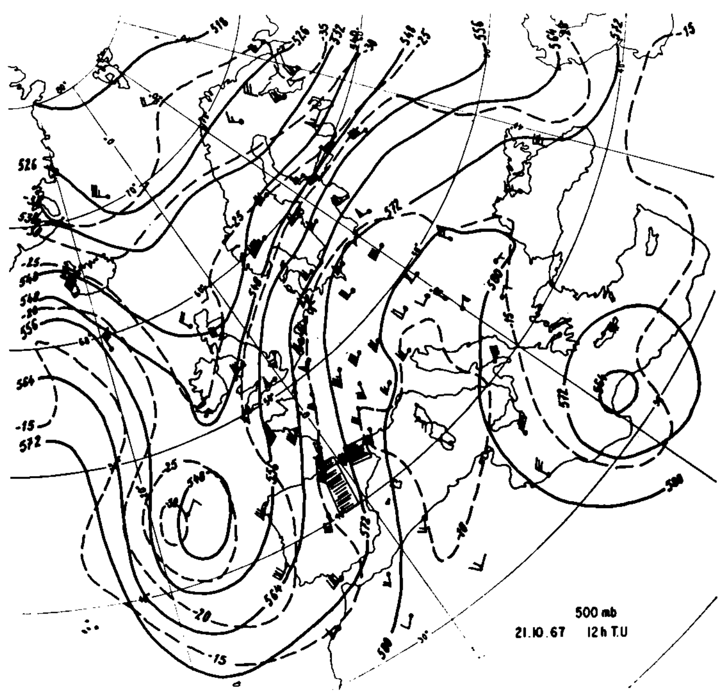

Fig. 12. Chart at 500 mb 21 October 1967 at 12H G.M.T.

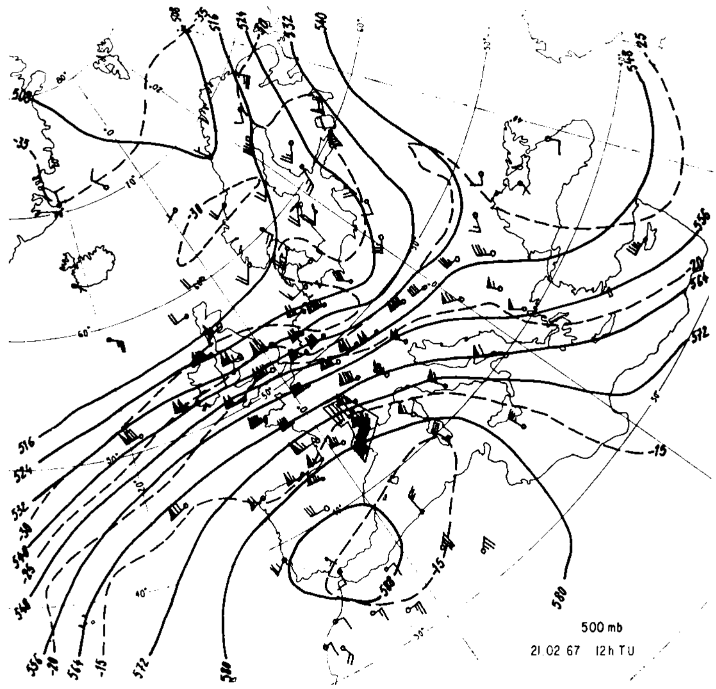

Fig. 13. Chart at 500 mb 21 February 1967 at 12H G.M.T.

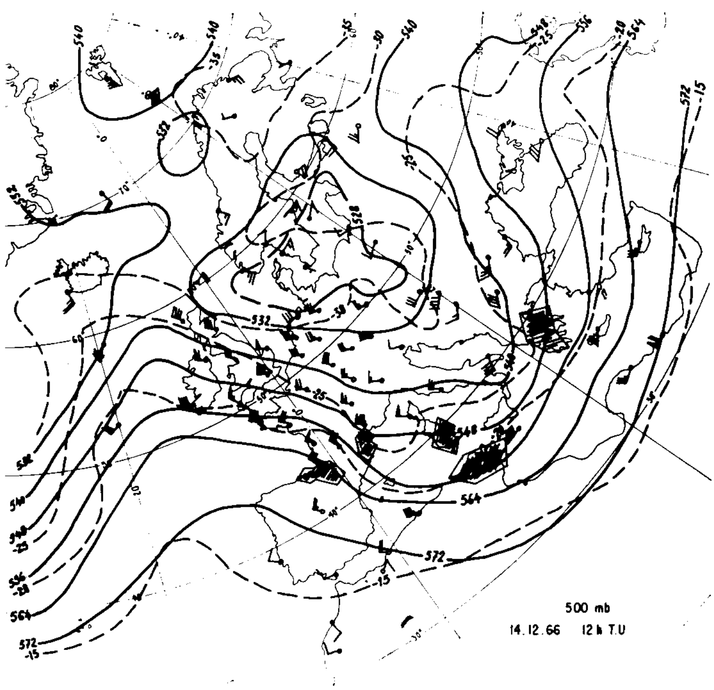

Fig. 14. Chart at 500 mb 14 December 1966 at 12H G.M.T.

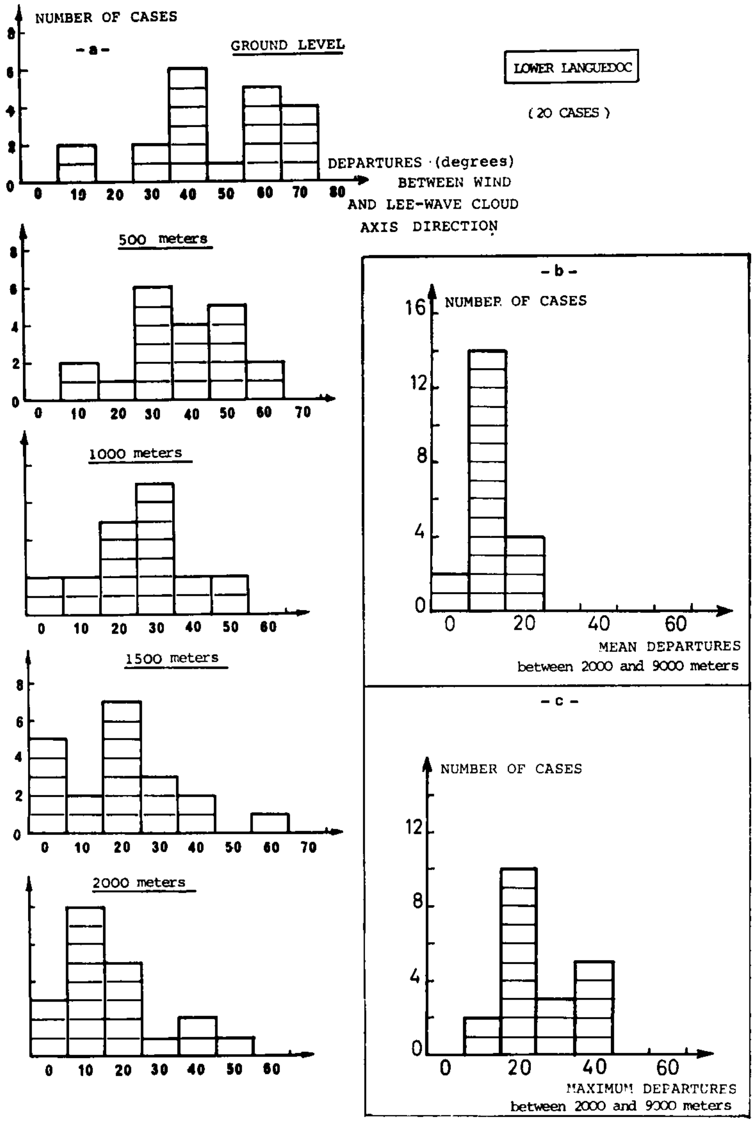

Fig. 15.

Figs. 15 and 16. 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. 15*a*), the histogram shows a maximum for departures whose values decreases when increasing altitude. At 2 000 m the maximum corresponds to values of ten degrees. Above this level (Fig. 15*b*) the mean depature 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 9 000 m, we can see that it can attain 40 degrees. The same figures for the Logroño area (Fig. 16*a* and 16*b*) show that the departures can frequently attain 40 degrees at 2 000 m. It is only at the altitude of 3 000 m that the histogram presents a sharp maximum for departures of 10 degrees, being then comparable to the histogram at 2 000 m for the Lower Languedoc area. Between 3 000 and 9 000 m the mean and the maximum departures are the same as those observed for the Lower Languedoc.

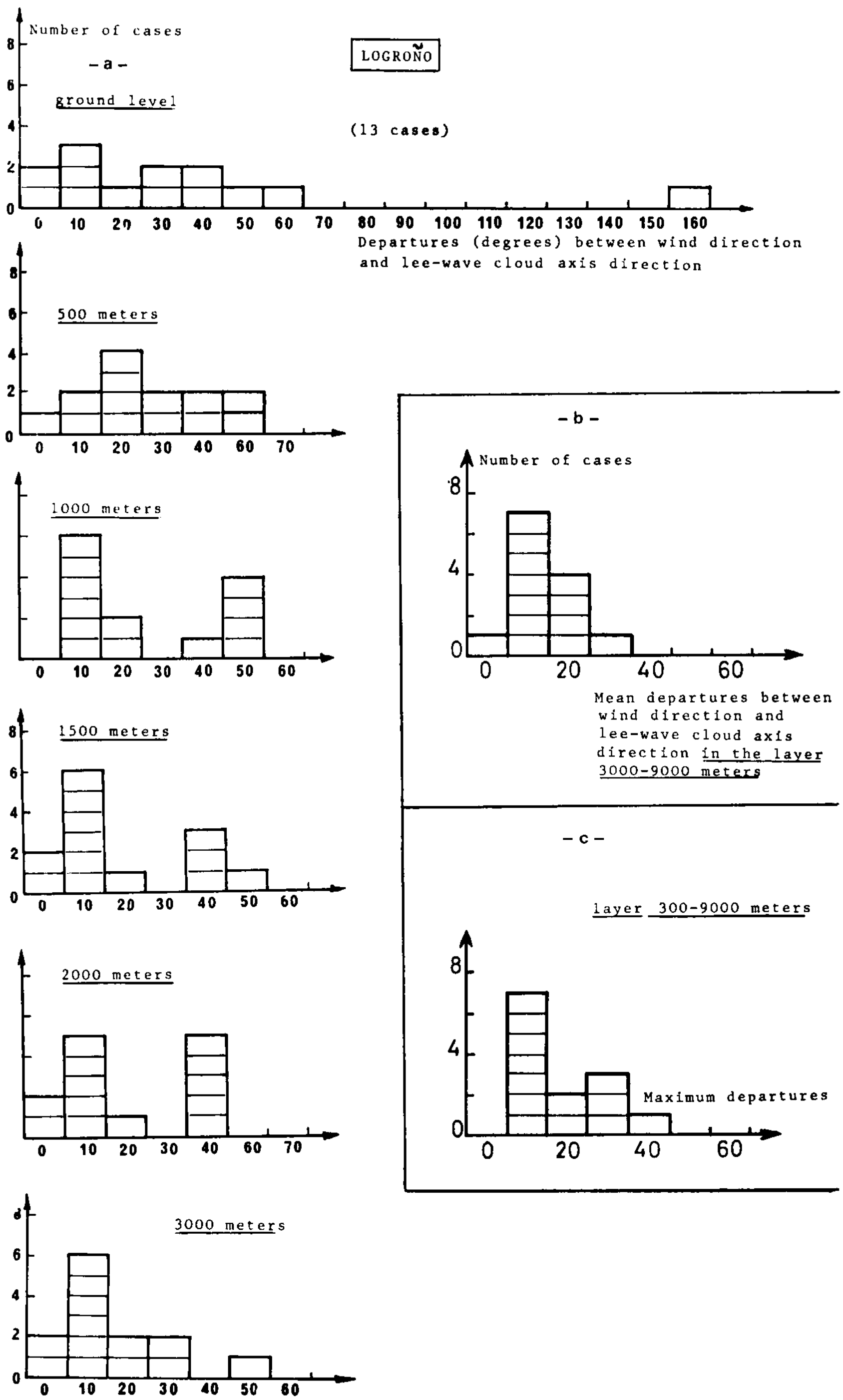
Number of cases
-a-
ground level
LOGROÑO
(13 cases)
Departures (degrees) between wind direction and lee-wave cloud axis direction
500 meters
1000 meters
1500 meters
2000 meters
3000 meters
-b-
Number of cases
Mean departures between wind direction and lee-wave cloud axis direction in the layer 3000-9000 meters
-c-
layer 300-9000 meters
Maximum departures

Fig. 16.

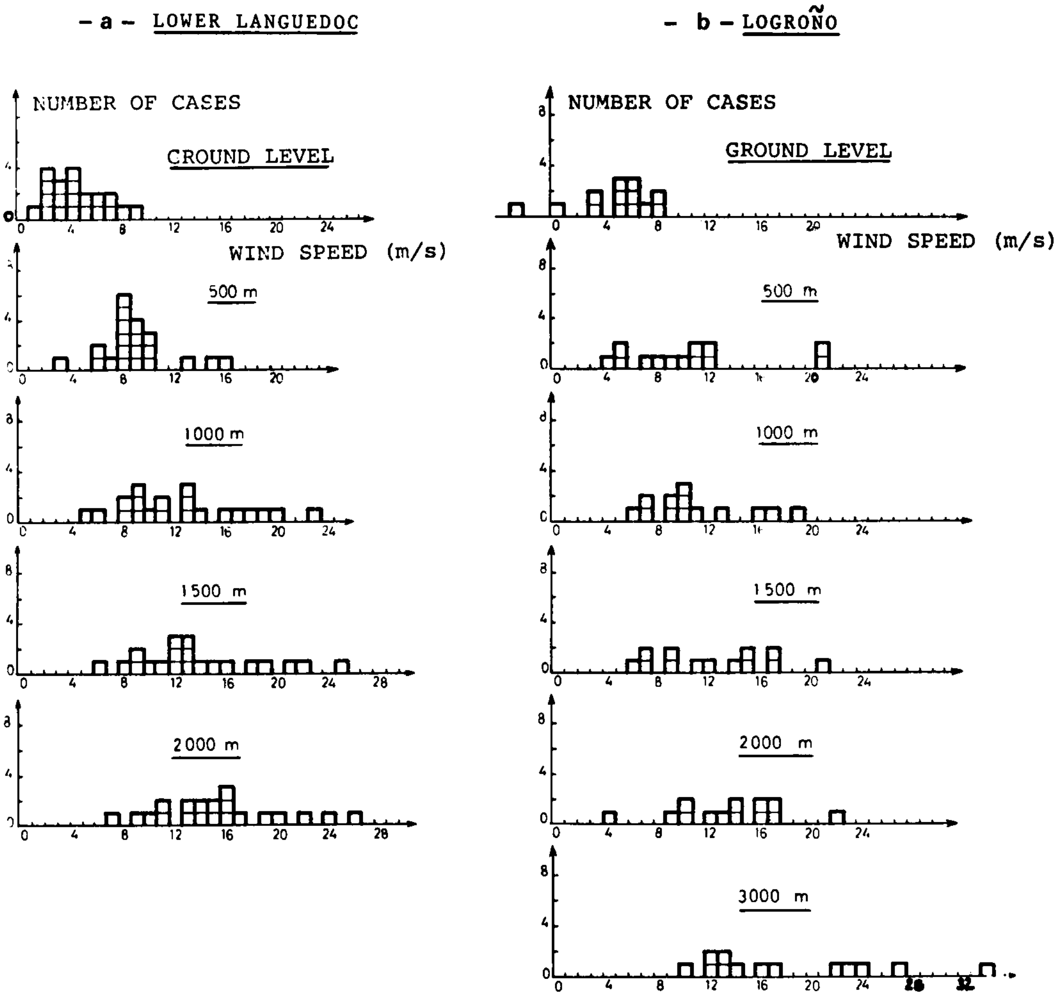

Fig. 17. Wind speed (measured in the direction perpendicular to cloud bands) at different levels. This figure gives the distribution of wind speed at the same levels as in Figs. 15 and 16. These histograms indicate a mean increase of wind speed with altitude. The minimum of wind speed at these different 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.

ward displacement of a ridge or trough can produce a similar displacement of such a system, or eventually its complete disappearance in one day).

3.2.2. *Relation to wind distribution.* Both theoretical and experimental researches on mountain lee-waves conclude that the vertical wind variation is an important parameter. It is generally admitted 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 suggested 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

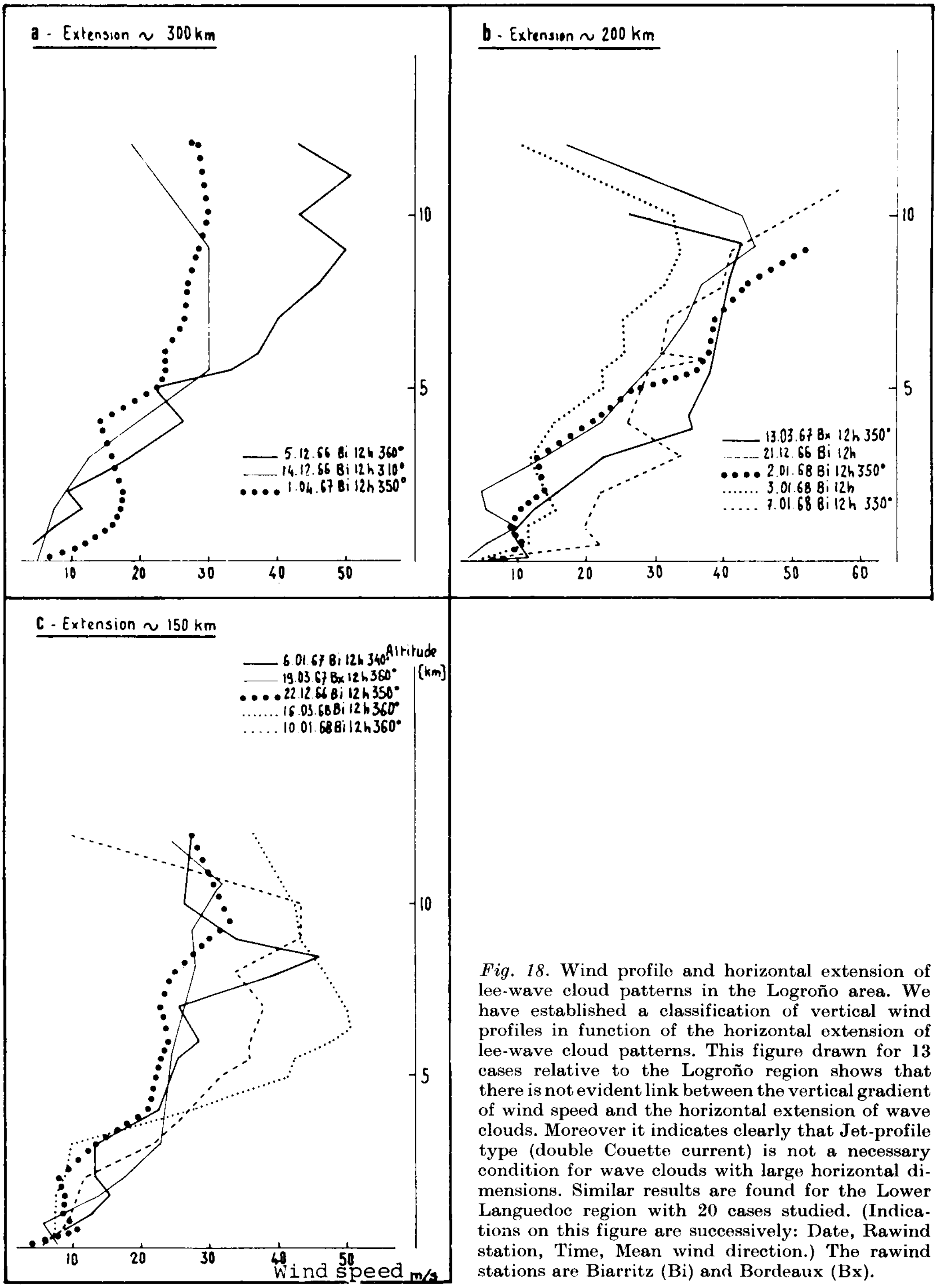

Fig. 18. Wind profile and horizontal extension of lee-wave cloud patterns in the Logroño area. We have established a classification of vertical wind profiles in function of the horizontal extension of lee-wave cloud patterns. This figure drawn for 13 cases relative to the Logroño region shows that there is not 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).

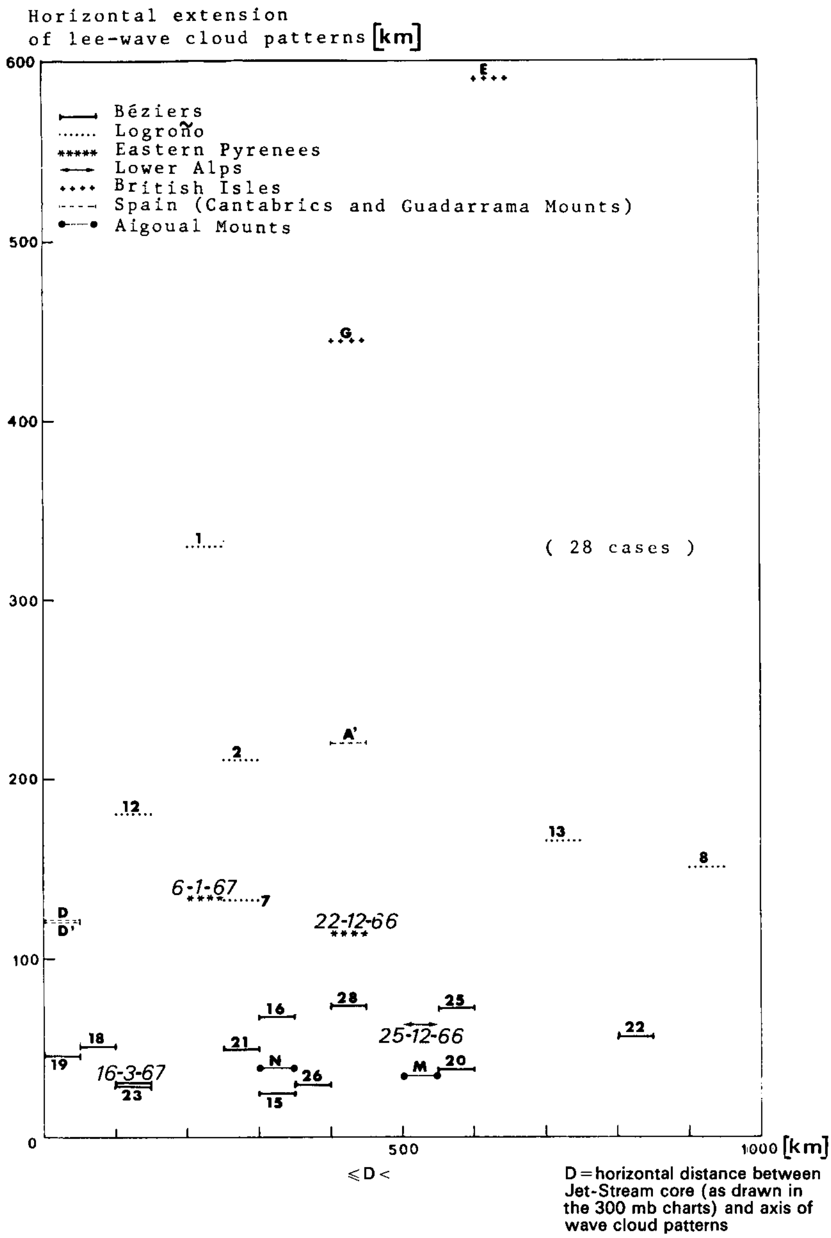

Fig. 19. Jet-stream and horizontal extension of lee-wave cloud patterns. In this figure we have plotted the values of horizontal extension of lee-wave cloud patterns versus the horizontal distance between wave cloud pattern axis and the Jet-Stream core as drawn on the 300 mb charts. We can see that wide 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.

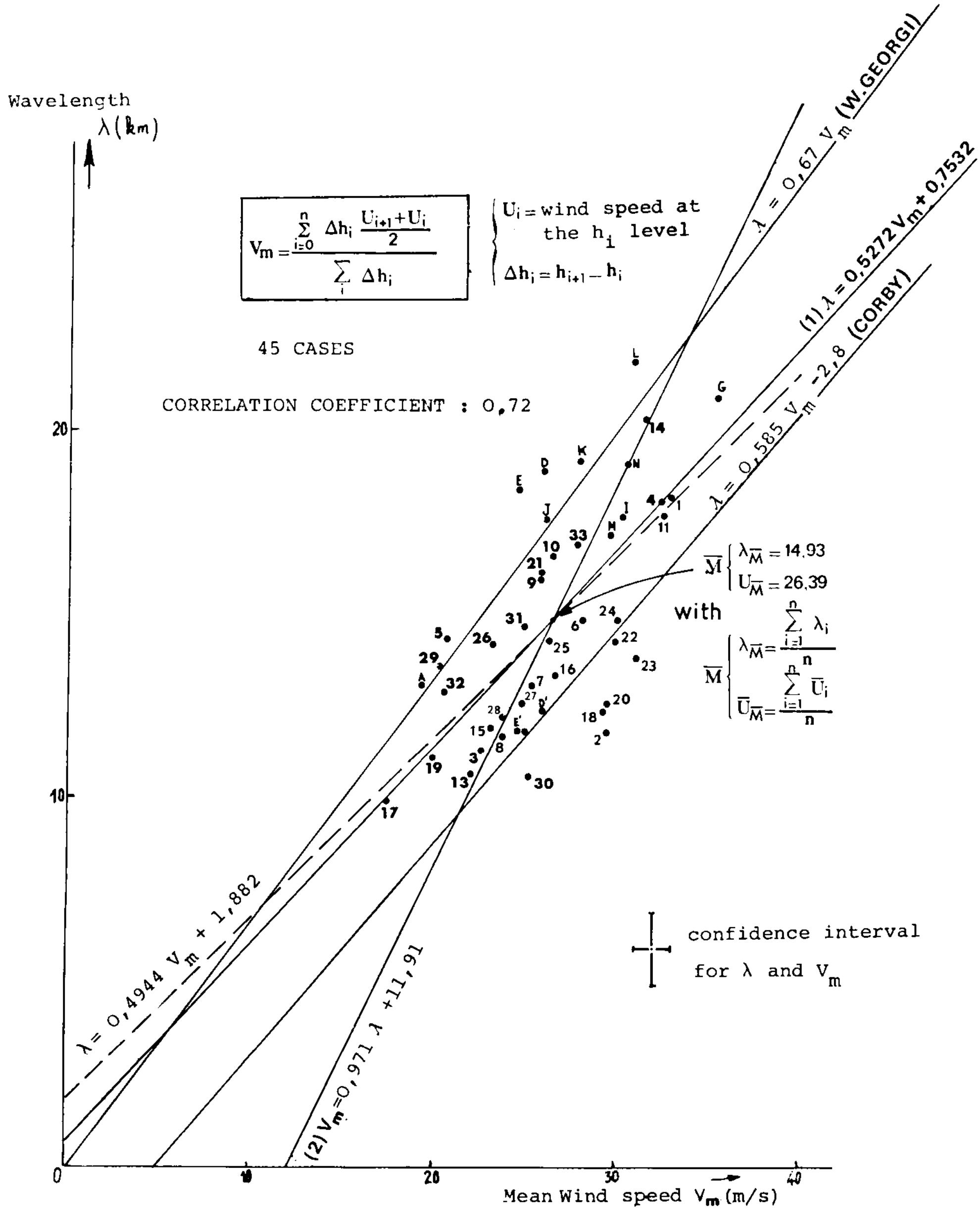

Fig. 20. Correlation between measured wavelengths (λ) and mean wind speed in the troposphere (V_m). Labelled points correspond to the cases indicated in Table 3 (Appendix I). V_m has been calculated with the formula written on the top of the figure. In this formula, U_{i+1} and U_i are the wind speed 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 this 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.

average speed from the spacing of the cloud bands measured on satellite pictures (Fritz, 1965).

We compared these various results to wind data concerning cloud-band cases, and our conclusions are as follows:

(i) 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.

(ii) Band direction seems closely related to wind direction in altitude, more so than to the wind direction at lower levels (Figs 15 and 16). 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.

(iii) From the minimal speeds at such levels we can deduce the threshold speed for each mountain, namely 6 m/s in Lower Languedoc 10 m/s in the Logroño region (Fig. 17).

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

(v) There is no clear relationship between the vertical profile of this wind component and the vertical or horizontal extent of lee-waves (Figs 18 and 19).

(vi) For 45 cases of wave-type clouds, we measured the cloudband spacing and computed the average wind speed in the troposphere. The graph of the first of these quantities versus the second (Fig. 20) suggests a positive linear correlation (the wavelength increasing with average wind speed), but with a rather small coefficient: 0.72, against 0.91 found by Corby but bearing 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 from its normal value. In these conditions it seems difficult to actually 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-waves clouds cannot be related to a specific type of frontal conditions (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).

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 cloud waves are observed, the vertical profiles of potential temperature show a common feature: above a quasi-neutral layer (small or even negligible stability) extending from next to the ground 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, topped by less stable air.

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 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 1969–70) were conducted in order to obtain informations on the vertical variation of the amplitude of the waves with the vertical distribution of static stability. The recorded meas-

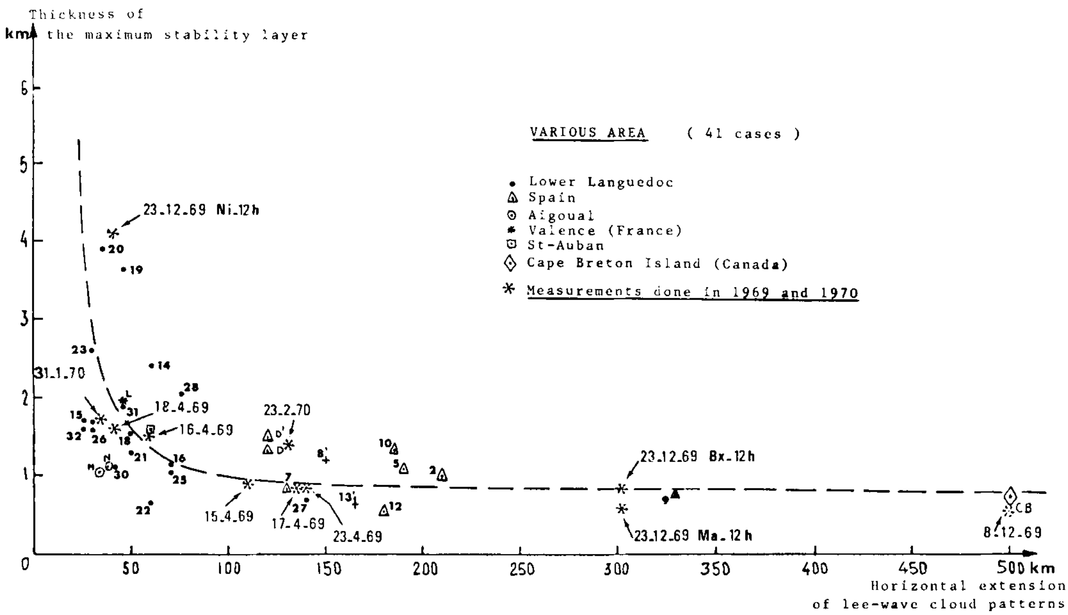

Fig. 21. Influence of thickness of the maximum stability layer on lee-wave cloud pattern horizontal extension.

urements 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).

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.

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 considered site. Therefore, it was legitimate to study the possible influence of regional geomorphology, as well on the formation of banded clouds as on their horizontal extent.

It is interesting to correlate the existence of areas particularly favourable to the occurrence of the phenomenon, with a theory by Professor P. Queney on meso-scale orographic pertrubations. This theory (P. Queney, 1962) indicates that: "with a mountain range the width of which exceeds 100 km, there is a predominant dissymetric horizontal deformation of the streamlines associated with their vertical deformation. Fig. 23 shows a typical aspect of this horizontal deformation at some level of the lower troposhere, 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

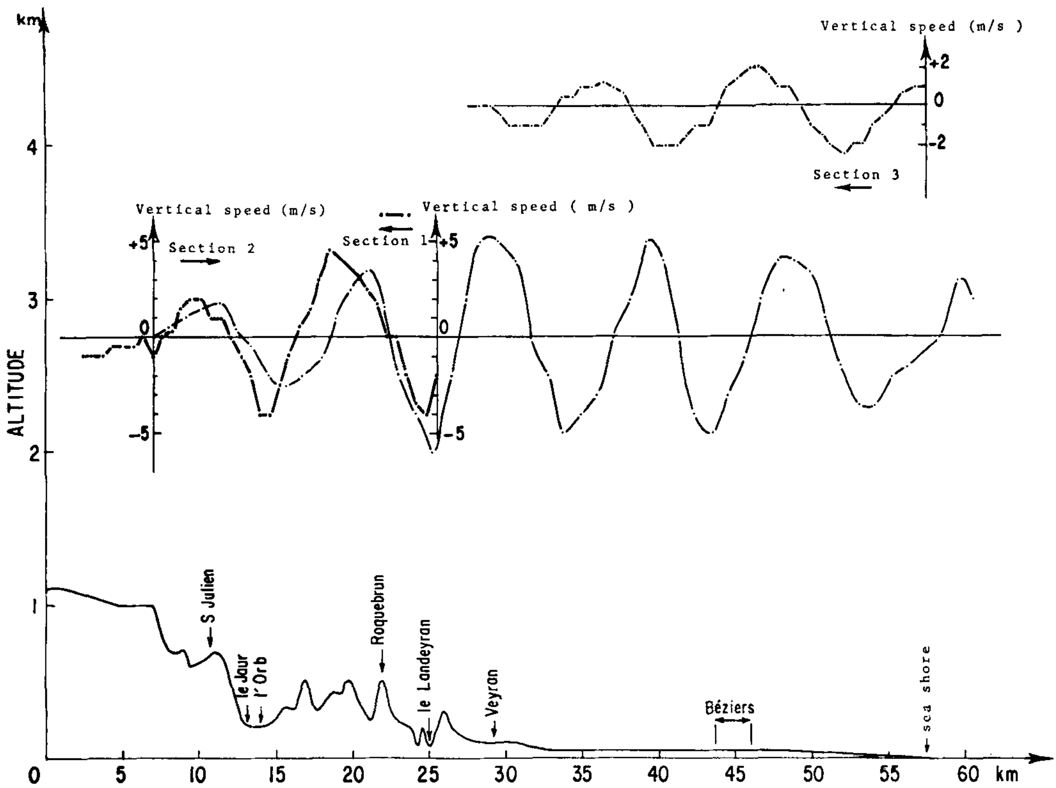

Fig. 22. Vertical component of wind speed in waves produced by Espinouse Mountains (January 16, 1970). These measurements were effected by an airplane belonging to the Pézenas Airclub, on January 16, 1970, between 15H06 and 15H47 local time, at mean altitudes of 2 800 m (section 1 and 2) and 4 200 m (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 plane did not pursue its measuring mission. Mean wavelength is about 10 km as well at 2 800 m as at 4 200 m. But vertical speed at 4 200 m is half the value at 2 800 m.

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. 24*a*), 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, Eastern Pyrenees and the Logroño area. In this latter case, the airflow concentration is due to the Cantabric mountains (Fig. 24*b*).

Lastly we propose an explanation to 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 inferior part or the northerly

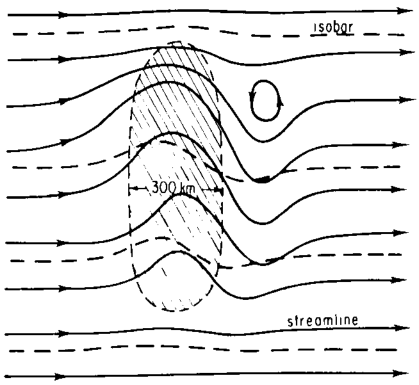

Fig. 23. Synoptic scale orographic perturbation of an uniform wind speed by a mountain range (according to P. Queney).

flow of the middle troposphere which is submitted to a foehn effect after passing over the Pyrenees.

Our above 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.

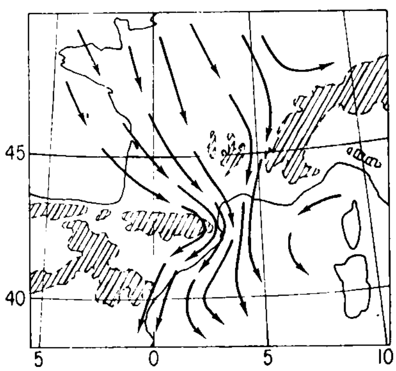

Fig. 24a. Mistral and Tramontane formation (according to P. Queney).

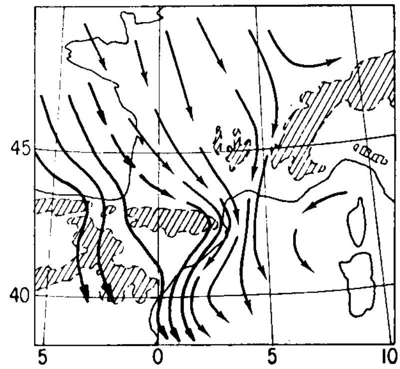

Fig. 24b. Application of the Queney's Theory: Concentration of the wind to the Eeast of the Cantabric range.

4. 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 so far, are in very good agreement with the conclusions of the present paper. This could be the subject of a further publication in this review.

Acknowledgements

Financial support was provided in part by la Météorologie Nationale, and by le Centre National de la Recherche Scientifique.

The Author expresses her sincere gratitude to Professor P. Queney, in whose department this work was done, for valuable discussions and help in the new version of this paper.

APPENDIX I

Table 3. *Lee-wave cloud pattern cases and soudings used for computation of the correlation coefficient*

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, TB = Toulouse-Blagnac, Ma = Madrid, Val = Valentia, Ni = Nîmes, Al = Aldergrove, LC = La Corogne

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	32.95	360	Bi-12h
2	13-03-67	10h35	Pamplona	36.6	11.9	29.48	350	Bx-12h
3	14-12-66	11h40	Pamplona	22.8	11.4	22.53	310	Bi-12h
4	16-03-68	10h38	Pamplona	33.8	18.2	32.4	360	Bi-12h
5	3-01-68	10h37	Pamplona	23.7	14.5	20.6	340	Bi-12h
6	10-01-68	11h08	Pamplona	29.3	15	28.1	360	Bi-12h
7	6-01-67	11h20	Pamplona	25.8	13.2	25.3	340	Bi-12h
8	19-03-67	10h19	Pamplona	24.2	11.8	23.7	360	Bx-12h
9	1-04-67	10h26	Pamplona	25.8	16.1	25.8[a]	350	Bi-12h
10	2-01-68	9h44	Pamplona	29.1	16.7	26.4 (9 km)	350	Bi-12h
11	7-01-68	10h23	Pamplona	33	17.8	32.5 (10.8)	330	Bi-12h
12	21-12-66	11h22	Pamplona	25.9	11.9	24.9	360	Bi-12h
13	22-12-66	10h49	Pamplona	21.98	10.75	21.88	350	Bi-12h
14	14-12-66	11h40	Béziers		20.4	31.5 (11.7)	330	TB-12h
15	21-12-66	11h18	Béziers	26.3	12	23.1 (11.6)	330	TB-12h
16	22-12-66	10h52	Béziers	28.6	13.5	26.6	340	TB-12h
17	24-12-66	11h29	Béziers	18.3	10	17.3 (11.4)	330	TB-12h
18	28-12-66	10h58	Béziers	31.3	12.5	29.2	330	TB-12h
19	29-12-66	10h27	Béziers	22.9	11.2	19.85	300	TB-12h
20	30-12-66	11h41	Béziers	29.8	12.7	29.3	320	TB-12h
21	6-01-67	11h17	Béziers	26.1	16.2	25.8	340	TB-12h
22	21-02-67	10h09	Béziers	30.5	14.4	29.9	290	TB-12h
23	2-03-67	9h49	Béziers	31.35	14	30.97	300	TB-12h
24	18-03-67	9h47	Béziers	34.4	15	30	330	TB-12h
25	19-03-67	10h19	Béziers	27.64	14.4	26.2	340	TB-12h
26	20-03-67	10h54	Béziers	25.4	14.3	23.15	360	TB-12h
27	6-04-67	9h35	Béziers	25.4	12.7	24.74	310	TB-12h
28	1-11-67	11h18	Béziers	24.4	12.3	23.8	310	TB-12h
29	29-11-67	9h59	Béziers	21.31	13.7	20.19	320	TB-12h
30	3-01-68	10h37	Béziers	27.2	10.7	25.1	340	TB-12h
31	4-01-68	9h36	Béziers	27.1	14.8	24.9	340	TB-12h
32	5-01-68	10h30	Béziers	21.2	13	20.43	330	TB-12h
33	25-12-68	11h09	Béziers	29.6	17	27.9	320	TB-12h
A′	13-12-66	12h13	Spain (NW)		13.2	19.3[b] (9.2)	320	Ma-12h
D	5-01-67	11h51	Guadarrama		19	25.9 (7.2)[c]		LC-12h
D′	5-01-67	11h51	Cantabrics		12.5	25.9		LC-12h
E	22-12-66	10h52	British Isles		18.5	14.5[a]	320	Alder-12h
E′	22-12-66	10h52	British Isles		12	24.5[a]	310	Alder-12h
G	21-12-66	11h25	British Isles		21	35.5[a]	330	Alder-12h
I	14-12-66	9h56	Gafsa		17.8	30.2	320	Gafsa-12h
J	14-12-66	9h56	Sardinia		17.7	26.05[a]	310	Ajaccio-12h
K	3-01-68	10h40	Ireland		19.3	27.9 (11.3)	330	Val.-12h
L	19-03-67	10h19	Valence (Fr)		22	30.97	360	Lyon-12h
M	19-03-67	10h19	Aigoual		17.3	29.71	360	Ni-12h
N	20-03-67	10h54	Aigoual		19.2	30.6	360	Ni-12h

[a] Interpolated from charts.
[b] La Corogne would be preferable but stopped at 4 200 m.
[c] The Madrid sounding at 12h G.M.T. stopped at 7 200 m.

APPENDIX II

Table 4. *Lee-wave cloud pattern cases and soudings used for computation of* β_m

Date	Cases	Location	Soundings		β_m	λ (km)
$V_m = 20$ m/s						
29-12-66	19	Béziers	Nimes	12h	1.21×10^{-5}	11.2
5-01-68	32	Béziers	Nimes	12h	1.21×10^{-5}	13
13-12-66	A′	Spain (NW)	La Corogne	12h	1.14×10^{-5}	13.2
$V_m = 25$ m/s						
6-01-67	7	Logroño	Madrid	12h	$1.49\ \ 10^{-5}$	13.2
21-12-66	12	Logroño	Bordeaux	12h	1.37×10^{-5}	11.9
4-01-68	31	Béziers	Nimes	12h	$1.29\ \ 10^{-5}$	14.8
6-04-67	27	Béziers	Bordeaux	00h	1.39×10^{-5}	12.7
3-01-68	30	Béziers	Nimes	12h	1.24×10^{-5}	10.7
$V_m = 26$ m/s						
22-12-66	16	Béziers	Nimes	12h	1.39×10^{-5}	13.5
19-03-67	25	Béziers	Nimes	12h	1.37×10^{-5}	14.4
1-04-67	9	Logroño	Madrid	12h	1.03×10^{-5}	16.1
6-01-67	21	Béziers	Nimes	12h	1.69×10^{-5}	16.2
2-01-68	10	Logroño	Madrid	12h		16.7
			Bordeaux	00h	1.24×10^{-5}	
5-01-67	D′	Cantabrics	La Corogne	12h	1.43×10^{-5}	19
	D	Guadarrama	Madrid	12h	$1.29 > 10^{-5}$	12.5
$V_m = 30$ m/s						
13-03-67	2	Logroño	Madrid	12h	1.24×10^{-5}	11.9
28-12-66	18	Béziers	Nimes	12h	1.35×10^{-5}	12.5
30-12-66	20	Béziers	Nimes	12h	1.1×10^{-5}	11.7
21-02-67	22	Béziers	Nimes	12h	1.28×10^{-5}	14.4
18-03-67	24	Béziers	Nimes	12h	1.48×10^{-5}	15
19-03-67	M	Aigoual	Nimes	12h	1.37×10^{-5}	17.3
20-03-67	N	Aigoual	Lyon	12h	1.29×10^{-5}	19.2
Other points						
22-12-66	13	Logroño	Bordeaux	00h	$1.42\ \ 10^{-5}$	10.7
21-12-66	15	Béziers	Nimes	12h	1.26×10^{-5}	12
22-12-66	E′	British Isles	Shanwell	12h	1.18×10^{-5}	12
21-12-66	G	British Isles	Shanwell	12h	1.36×10^{-5}	21
19-03-67	L	Valence (Fr)	Lyon	12h	$1.43\ \ 10^{-5}$	22

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ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ ВОЛН ЗА ГОРАМИ С ПОМОЩЬЮ СПУТНИКОВЫХ ФОТОГРАФИЙ И САМОЛЕТНЫХ ИЗМЕРЕНИЙ

В этой работе суммируются результаты докторской диссертации, в которой проводится систематическое изучение влияния различных метеорологических факторов на возбуждение и характеристики волн за горами, особенно волн большой горизонтальной длины. Данные, используемые здесь, кроме классической метеорологической информации, взяты со спутниковых фотографий и дополнены квазиодновременными измерениями с самолетов или планеров. Анализ многих спутниковых фотографий, полученных на французской станции Ланнион в Бретани в течении трех лет (1966–1968 гг.), дал достаточно полное описание облаков в волнах за горами, видимых над Западной Европой и Северной Африкой, и привел к следующим выводам: 1. во всех рассмотренных случаях волн за горами отмечался слой высокой статистической устойчивости между 1 000 и 4 000 *м* над уровнем моря; 2. горизонтальная протяженность волн изменялась обратно пропорционально толщине этого сильно устойчивого слоя, который, таким образом, представляется служащим в качестве волновода, где захватывается почти вся энергия возмущений, вносимых в поток горами, точно также как обычные гравитационные волны возникают и остаются на поверхности спокойного слоя воды (так называемые «поверхностные волны»).