OBSERVATION OF LEE WAVES ABOVE THE PYRENEES (FRENCH-SPANISH 'PYREX' EXPERIMENT)

by B. Benech, J. L. Attie, A. Blanchard, P. Bougeault, P. Cazaudarre, A. Druilhet, P. Durand, E. Koffiand, P. Prudhomme (France) and D. S. Tannhauser (Israel)

Presented at the XXII OSTIV Congress, Uvalde, Texas, USA (1991)

I. INTRODUCTION

Lee waves have often been studied, recent experimental work has been done for instance by Brown[1] and by Hoinka[2]. We present here a case study for October 15, 1990 in the framework of the Pyrenees Experiment (PYREX[3]) an extensive measurement program with French and Spanish participation which took place in and around the Pyrenees during the period October 1 to November 30, 1990. Figure 1 shows the domain of interest for PYREX with the major geographical elements. The objective of the experiment was to study the mesoscale atmospheric influence of the Pyrenees and the local winds generated by this mountain chain under certain meteorological conditions. The long-term objective is to improve weather forecasting in the vicinity of mountain chains.

When the upper level wind is perpendicular to a mountain chain the accumulation of air on the upwind side of the relief creates a high pressure zone which slows down the incident flow. Part of the air is deflected upwards, giving rise to mountain waves. The waves are generally associated with a vertical flux of horizontal momentum extending to quite high altitudes, as a result the average wind speed downwind of the mountain is diminished. The waves attain considerable amplitude before dissipating into turbulence. Furthermore, the friction effect of the mountain causes a loss of kinetic energy to turbulence. A second part of the air is diverted laterally giving rise to a strong vertical wind shear in the vicinity of the relief. The acceleration of this flow downwind of the chain together with the inversion formed by the warm air descending from the crest of the chain can give rise to a violent flow near the surface very different from that at altitude (e.g. the AUTAN wind near Toulouse).

In the course of the PYREX period a case of SSW flow with lee waves was studied intensively using airplanes, constant volume balloons (CVB's) and sailplanes. The average wind direction (Figure 2a) was 200°; this is practically perpendicular to the axis of the Pyrenees. In addition, field data (pressure, temperature and humidity) were collected at various levels. The vertical velocities observed in the laminar flow were of medium strength, with a maximum value of 6 m/s.

II. THEORETICAL MODELING OF LEE WAVES

Both analytical and numerical modeling of lee waves has been done. A good reference for the state-of-the-art in 1981 is Atkinson[4], though the mathematics are not always clear in his book. An older, more rigorous but harder-to-read text is Alaka[5]. A thesis by Durran[6,7] has a good general introduction to the problem. We shall quote a few lines from these sources.

A. Analytical Modeling

This is usually confined to Linear (small amplitude) theory. The basis of modern treatments is the work by Scorer[8], who assumed for simplicity that a single mountain chain with a bell-shaped cross section triggers the waves.

Important for the existence and strength of lee waves is the altitude dependence of the Scorer parameter l^2

$$l^2 = \frac{g\beta}{U^2} - \frac{1}{U}\frac{\partial^2 U}{\partial z^2} \qquad (1)$$

where β is defined as $(\partial\theta/\partial z)/\theta$, θ is the potential temperature, g is the acceleration due to gravity, U is the horizontal wind speed, z is the altitude and l is a wavenumber. The second term of Eq. 1 measures the vertical variation of the wind shear; it is normally relatively small.

In a non-uniform airstream in which l decreases to-

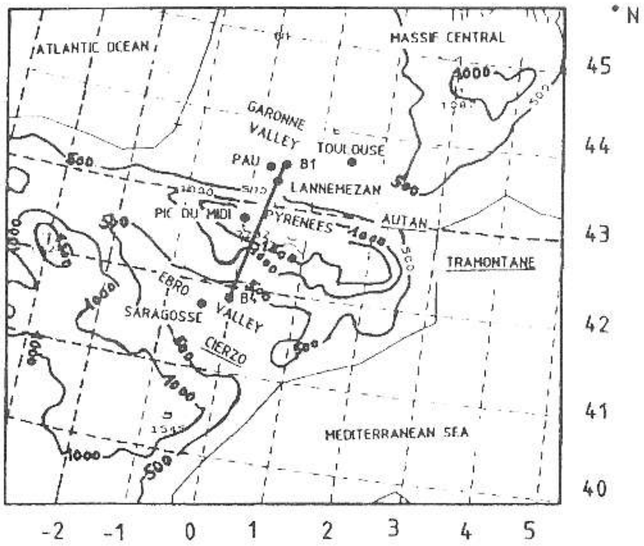

Figure 1. Domain of interest for PYREX with the major geographical elements. Altitudes are in meters. The names of local winds are underlined. Full circles indicate the location of the reference points B1and 4 mentioned in the text as well as the radiosonde stations.

wards higher altitudes the layer with lower l reflects the waves. There are, therefore, trapped at the lower level, giving rise to "trapped lee waves" (also called resonance waves) which can only exist for discrete wavenumbers and typically extend much further downstream than untrapped waves (Durran 1981, p. 27). The physics is similar to the trapping of light inside an optical fiber. an essential requirement for strong waves is marked stability (large ß) at levels where the air is disturbed by the mountain.

A two level structure of the Scorer parameter is therefore considered to be necessary for trapped lee wave formation, with l^2 lower > l^2 upper. A necessary criterion for the existence of waves developed by Scorer is often quoted (e.g. by Ralph, et al[9].), namely that (l^2 lower - l^2 upper) $> \pi^2/4H^2$ where H is the depth of the lower layer (see also Alaka p. 69 for this) but this seems to apply only to a strictly two dimensional model (Atkinson p. 63).

Sawyer[10] confirmed by numerical modeling that a low level maximum of l^2 is indeed favorable for lee wave formation but found also that other distributions of l^2 can give rise to lee waves.

Figure 2. Synoptic charts of October 15, 1990.
a. 500 hPa chart of 0000 UT.

Since the amplitude of real waves is too large to be created by linear theory, non-linear calculations have been done. However, as of 1981 such calculations were mainly applicable to incompressible fluids, though they did also show the atmospheric phenomena of rotors and hydraulic jumps (Atkinson[4]).

B. Numerical Modeling

A recent numerical work is by Xue and Thorpe[11] who discussed the effect of atmospheric moisture on lee waves. Previously Durran[7] treated the same problem.

C. Relation between Models and Reality

When any model is compared with measured wave parameters it should be remembered that:

- The models are usually two dimensional. In practice the mountain chain is not infinite and its cross section varies with y.
- The cross section of the mountain chain is never bell shaped as usually assumed.
- The air flow varies with time while models and interpretation of measurements, which extend usually over a few hours, assume steady state. In this connection a recent paper by Ralph, et al.[9] is of interest; the authors observed directly the temporal change of the spatial structure of trapped lee waves, the steady state lasting less than one hour.

III. THE SYNOPTIC METEOROLOGICAL SITUATION

Figure 2a shows the synoptic situation map of October 15, 1990 at 1200 UT. A minimum of pressure south of Ireland and a pronounced meridional Thalweg is seen. On the east side of this atlantic Thalweg a strong south to south-west wind blew at 15 to 25 ms^{-1}, over Spain and southern France, quasi perpendicular to the chain of the Pyrenees.

On the surface, the large depression zone situated over the atlantic has one minimum (990 hPa) extending from north Ireland to west of the Bretagne and a second minimum (also 990 hPa) situated west of Corogna (Spain) at 45°N 20°W. The cold front connected with the first minimum reached the French coast near 1200 UT (Figure 2b). The surface flow over most of Spain is from southwest at 5 to 8 ms^{-1} and is south-easterly in the Ebro Valley (see Figure 1). On the French side the Autan wind is well established in the region of Languedoc and the plain of Toulouse, the surface wind being SE over almost all the southwest of France. This SE flow is governed by the atlantic depression.

Near the Pyrenees, the isohypses at 500 hPa (Figure 2a) and the isobars at ground level (Figure 2b) are practically perpendicular to the mountain chain from 0000 UT to 1200 UT, which includes the period of measurements. The gradient of pressure along the axis of the Pyrenees was about 4 hPa/100 km (Figure 2b). The proximity of the cold front which accentuated the southerly component of the synoptic flow could play a role in the stability of this flow. Behind the cold front the air becomes colder and less stable. Radiosonde data of Saragossa (100 km upwind of the Pyrenees), of Pau (50 km downwind) and of Toulouse (90 km downwind) show a fairly homogeneous flow direction of 200°. This flow was maintained during the experimental phase

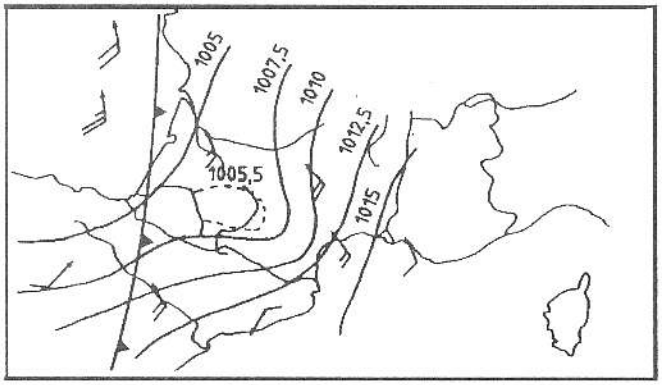

Figure 2. Synoptic charts of October 15, 1990.
b. Surface pressure chart for the region of the Pyrenees at 1200 UT.

between 0600 and 1200 UT.

IV. EXPERIMENTAL TECHNIQUE

The experimental means used for the study of the flow above the Pyrenees were concentrated in the central part of the chain, along a line of 200 km extending from B1(43°35′N, 0°35′E) to B4 (41°50′N, 0°00′E), see Figure 1. This line is almost perpendicular to the chain. They included:

15 ground stations equipped with microbarographs.

Three Radar Wind Profilers, located at Ainsa, Spain (43°26′N, 0°09′E), Saint Lary, France (42"49′N, 0"17′E) and Lannemezan, France (43"08′N, 0"25′E).

Three instrumented airplanes based in Toulouse: a FOKKER 27, a MERLIN I and a FALCON.

A site for launching CVB's on the Pic du Midi (42°56′12″N, 0°08′46″E).

Three sailplanes based at Saint Girons, France (43°00′N, 1°09′E). Since this work concerns lee waves which are assumed to be stationary, only the airborne equipment (airplanes, sailplanes and balloons) is relevant. We describe therefore their properties.

A. Instrumented Airplanes

The FOKKER 27 belonging to a group of French institutes can measure mean and turbulent components of wind, temperature and moisture, and also radiation and cloud microphysical properties. It carries the Lidar LEANDRE which determines the spatial distribution of the atmospheric particles used as dynamic tracer. Instrumentation and output data available are described in a report of the Institute National des Sciences de l' Univers[12] (1987). The absolute accuracy of temperature is 0.2°C, of static pressure 0.15 hPa, of horizontal wind speed components 1.0 ms^{-1} and of vertical velocity 0.5 ms^{-1}. The relative errors of temperature are 0.05°K, of wind speed 0.1 ms^{-1} and of static pressure 1 hPa. The data of the FOKKER are originally acquired at 32 Hz and then averaged to an effective frequency of 1 Hz for storage in a data bank. The data given here have been averaged over 10 seconds.

The Merlin IV of the French Meteorological Office and the FALCON of the Deutsche Luft und Raumfahrt have the same capabilities as the FOKKER except for the airborne lidar. In the present paper we do not use data measured by these two airplanes.

B. Constant Volume Balloons

The envelopes of such balloon s are made from inelastic mylar, the volume is held constant through a pressure slightly above that of the chosen flight level. The weight of the balloon is adjusted to give an apparent density equal to that of the air at the flight level. This results in a constant density (isopycnic) surface except when vertical air currents act on it or when its density changes slightly (Benech, et al.[13]).

The balloons used during PYREX were cylindrical, 6m long and 0.6m diameter. They could carry a radiosonde of 500 gr to an altitude of 5000m. The balloons were released from the Pic du Midi and tracked by a radar at Lannemezan. The radar data give directly the horizontal wind speed; the radiosonde transmits data on pressure, temperature and humidity.

C. Sailplanes

Three two-seater sailplanes (a Marianne belonging to the French Air Force, one Janus CM belonging to a local club and a second Janus CM belonging to the French Gliding Federation) participated in the experiment; they carried the standard sailplane instrumentation.

The altitude, airspeed and variometer readings were corrected after the flight using the meteorological data for the measurement period and the known sink rate of the sailplanes.

The mission of the sailplanes was to obtain a semi-quantitative point of view of the lee wave situations and to verify the two-dimensionality of the wave along the chain of the mountains.

D. Experimental Strategy

The airplane tracks were all in the same vertical plane and extended between points B1 and B4. Thus the FALCON flew six horizontal paths between 6300 and 11700m. The FOKKER flew four horizontal paths between 3900 and 5400m. Finally the MERLIN flew north and south of the relief on axes perpendicular to the chain between 100m agl (security level) and 2000m. In addition this airplane flew above the relief on axes parallel to the mountain between FL 130 and FL 170, taking into account the form of the relief.

The CVB's released from the Pic du Midi flew in a vertical plane close to that of the airplanes. They give more or less the Lagrangian behavior of the air while the airplanes give approximately Eulerian data. On October 15 three balloons were released successively to heights between 3000 and 5000m.

The sailplanes documented the flow in the vicinity of the principal axis. Observations were made on two planes parallel to the principal plane and about 50 km on each side of it at altitudes between 4000 and 6000m. Finally, one sailplane measured at similar altitudes in a plane parallel to the chain staying within the first lee wave.

V. DESCRIPTION OF THE THERMODYNAMIC FIELD AND THE LEE WAVE PROPERTIES

The description of the thermodynamic structure of the flow across the Pyrenees is based mainly on the data of the FOKKER 27. Figure 4 shows the flight paths above the relief parallel to the axis B1-B4 (direction 200°).

Between 4000 and 6000m the fields of interpolated potential temperature values (Figure 3a) and of water content (Figure 3b) show a marked zone of subsidence after the air has crossed the Pyrenees. The variations at 5000m of potential temperature are of order 2°C, those of water content are 0.3 to 0.4 g/kg.

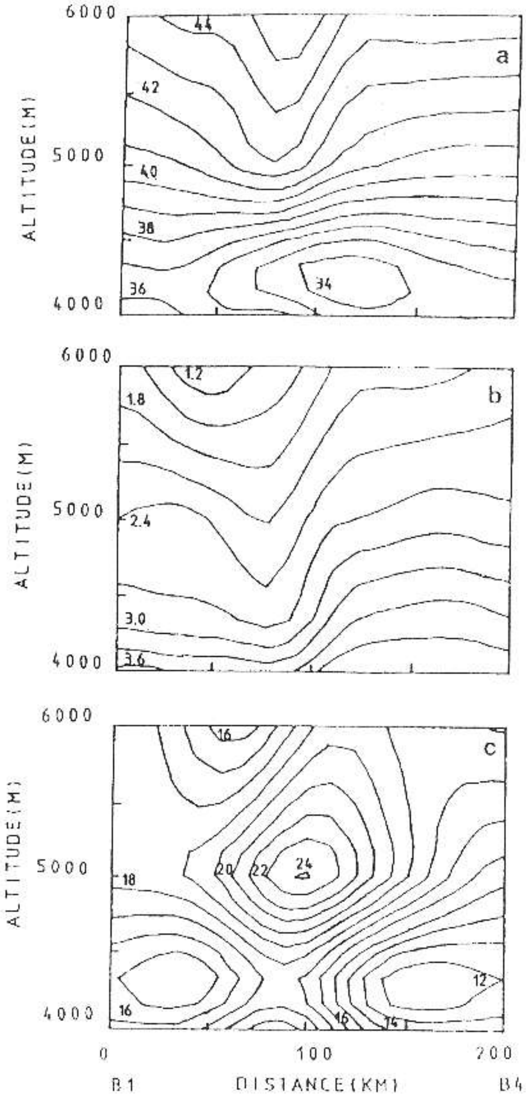

Figure 3. Field of thermodynamic variables on 15/10/90 for a vertical plane containing the axis B1-B4. The data were deduced from measurements of the FOKKER 27.
a. Potential temperature in °C.
b. Absolute humidity in g/kg.
c. Horizontal wind speed in m/s in direction 4-B1 (200°).

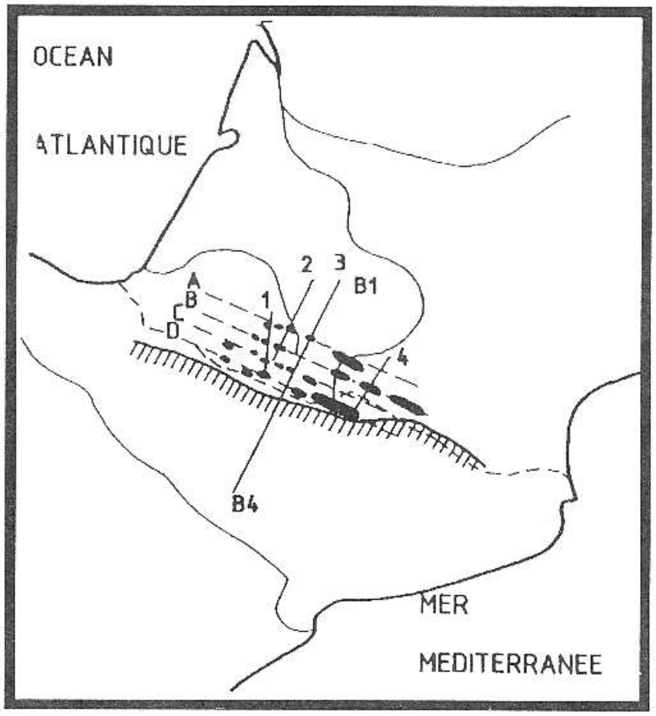

Figure 4. Structure of the wave field downwind of the Pyrenees deduced from sailplane observations. The observed zones of ascendence of the waves are marked in black. The axes of flight of the sailplanes (lines A, B, C, D, 1 and 4) of the airplanes (3) and of the constant volume balloons (2) are also given.

The component of wind speed along B4-B1 (Figure 3c) indicates an acceleration of about 4 m/s after crossing the mountain. This acceleration seems to diminish with height.

All parts of Figure 3 are based on a numerical filtration which suppresses waves with $\lambda \leq 15$ km. The structure of these thermodynamic fields indicates that the air in which the lee waves develop has descended from higher to lower layers. This affects the thermal structure and as a result the stability, giving rise to a variation of the Brunt-Väisäla Frequency and the Froude number on crossing the mountain chain.

The wave structure observed in the lee of the mountain consists essentially of four main regions of ascendance parallel to the mountain chain (Figure 4). The different experimental means (airplanes, balloons and sailplanes) give the same position of these four waves. The black zones shown in this figure are zones of rising air deduced from sailplane observations. These observations which extended along the axis of the mountain chain show that the wave system seemed to be better organized in the eastern part of the domain of observation, where the wave areas are practically continuous along transverse axes. In the western part of the domain the wave areas are less continuous. The mean wavelength deduced from the position of the waves is about 10 to 11 km. Figure 4 shows also the flight paths of the airplanes (B1-B4) and of the CVB's. One notes that the quantitative documentation of the waves is done in the zone where the wave system is not very well organized.

The hatched portion of Figure 4 is the region where the clouds were blocked by the relief.

Figure 5 shows variations of the potential temperature and the vertical velocity along the axis B1-B4 for the various levels flown by the FOKKER. For both parameters the wave system is easily discerned between 4200 and 5400m.

Comparison of the spatial variation of the various horizontal profiles shows differences between them which are due mainly to the phenomenon being nonstationary. It should be remembered that the measurements were made not long before a cold front arrived in the experimental area early in the afternoon (Figure 2b). Along the flight path the temperature varies by 3 to 4°C, the water content by 0.2 to 0.4 g/kg and the

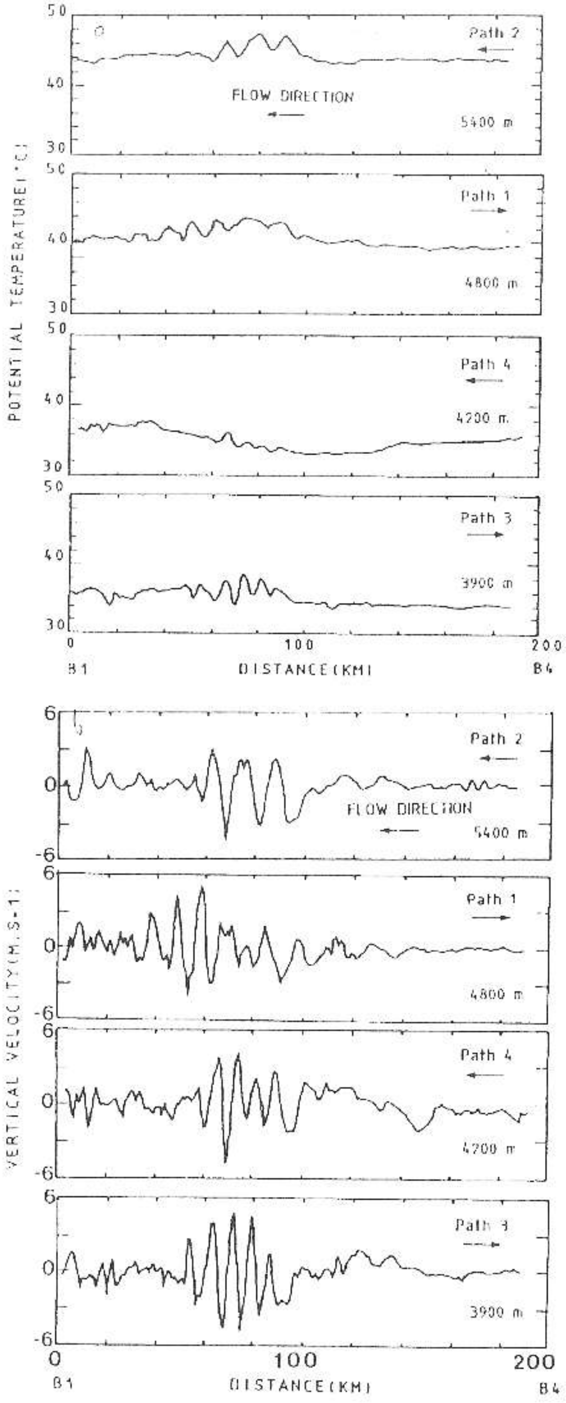

Figure 5. Characteristics of the waves deduced from measurements of thed FOKKER 27 at four altitudes.
a. Potential temperature.
b. Vertical velocity in m/s.

vertical airspeed by + or - 3 m/s.

We show in Figure 6a the mean values of vertical velocity for the three or four waves detected by the FOKKER at each flight level and the same information deduced from the balloon flights. The vertical velocities measured by the CVB's at lower altitudes are larger than those measured by the FOKKER. It is clearly apparent that the vertical velocities decrease with altitude.

The wavelength deduced from the data of Figures 4 and 5 is shown in Figure 6b. It varies with altitude, being 9 to 12 km at altitude 4000-5000m and 8 to 10 km at 3000-4000m.

VI. ANALYSIS AND COMPARISON WITH OTHER PAPERS

We show in Figure 7 the Scorer parameter l^2 calculated from radiosonde data for Saragossa, Toulouse and Pau for 0600 UT which is close to the beginning of the measurement period. The radiosonde data were smoothed by three passes through a three point averaging program. For U we used the wind velocity component in direction 200 degrees, the average wind direction at altitude on this day.

It is seen that l^2 for Saragossa at 0600 UT has approximately the classic form of a high value at low level and a lower value higher up. If we take $l^2 = 0.3$ at 5 km and

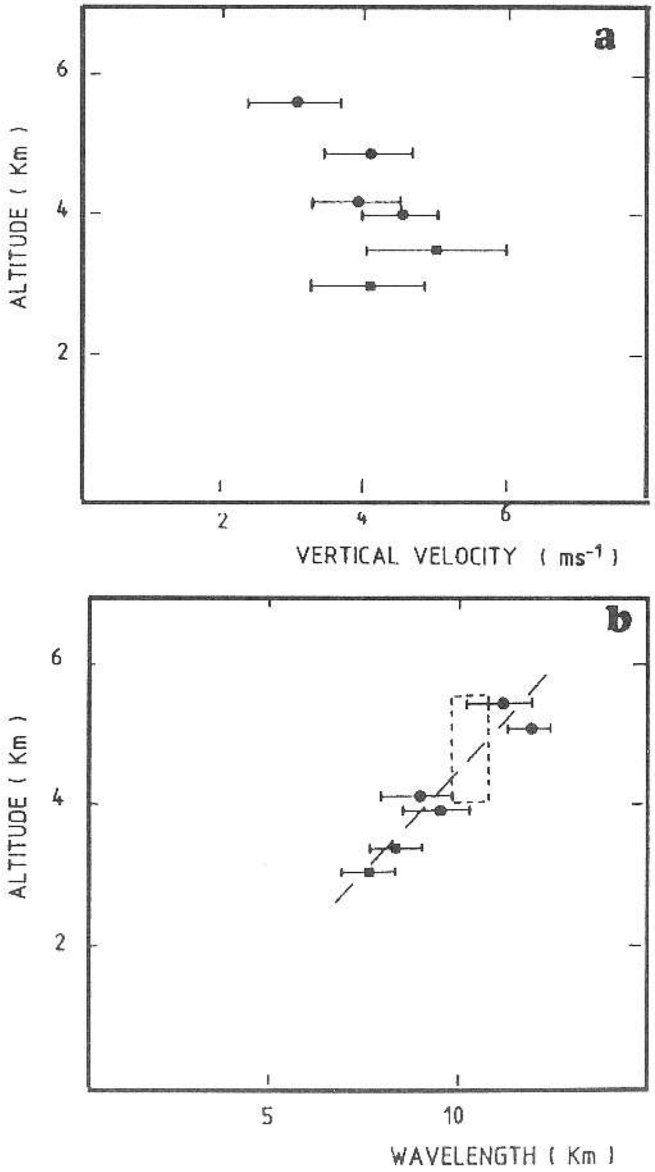

Figure 6. Vertical velocity (a) and wavelength of the waves (b) deduced from airplane (•) and balloon (m) measurements.

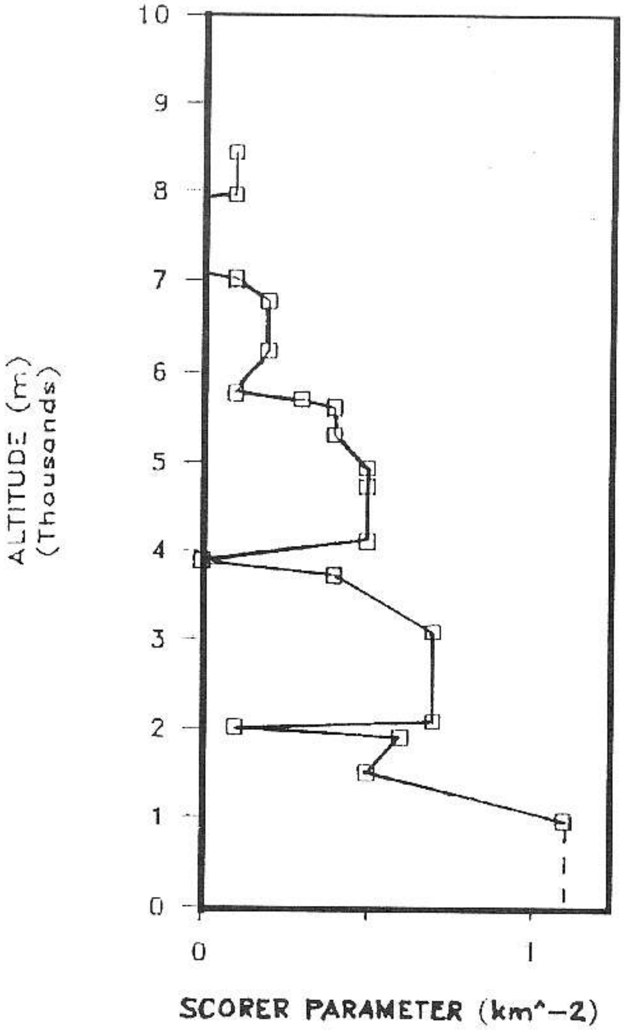

Figure 7. The Scorer parameter calculated from radiosonde data at Saragossa on 15/10/90 at 0600.

0.6 at 2.5 km we calculate a wavelength of about 10 km, in good agreement with the observed values. Alternatively, we can use the values given in Figure 3 to calculate the Scorer parameter at h=4 km just downwind of the Pyrenees, this also gives a wavelength of 10 km. It appears that the temperature profile of 0600 at Saragossa is advanced more or less unchanged to the experimental zone.

Since the meteorological situation was not necessarily stationary one cannot draw conclusions regarding the tilting of the wave crests with altitude. An indication of tilting of the planes of equal phase can be obtained indirectly from the fact that the horizontal wind velocity varied with a wavelength very close to that of the vertical velocity. This points towards waves propagating – with respect to the moving air stream – at an angle to the horizontal. For such waves the oscillation of the air particles would have a horizontal component, explaining the above observation.

The spreading out of the lines of potential temperature in the lee of the chain as observed by Hoinka[2] was present but less pronounced than in the case of March 23, 1982.

Brown[1] analyzed five wave event over the British Isles and found good agreement between the calculated and the experimental values of wavelength and wave amplitude.

In a study of lee waves over the Appalachians Smith[14] used both linear and nonlinear analysis. He concludes that the wave length of lee waves is well predicted by linear theory but the amplitude is not.

A more detailed analysis of the data, including those of the other airplanes, will be published later.

ACKNOWLEDGMENTS

The PYREX project is a joint program of METEO-FRANCE and Instituto Nacional de Meteorologia (INM, Madrid). It is also supported by Institut National des Sciences de l'Univers (Paris), CNES, EDF, Region Midi Pyrenees and DLR (Munich).

The authors would like to thank all the participants who helped with the preparation and running of the experiment. Special thanks are due to the IGN group and the FOKKER maintenance section of INSU. We acknowledge gratefully the radiosonde data supplied by CNRM group 4M and the Spanish Meteorological Service as well as the help of R. Benoit in the preparation of the sounding data from group 4M and INM.

REFERENCES

1. P. R. A. Brown, Aircraft Measurements of Mountain Waves and their Associated Momentum Flux over the British Isles.
2. K. P. Hoinka, Observation of a Mountain Wave Event over the Pyrenees, Tellus, 36A, 369 (1984) and Corrigendum, ibid 38A, 93 (1986).
3. P. Bougeault, A. Jansa Clar, B. Benech, B. Carissimo, J. Pelon and E. Richard, Momentum Budget over the Pyrenees: The PYREX Experiment, Bull. Am. Meteor. Soc. 71, 806 (1990).
4. B. W. Atkinson, Meso-scale Atmospheric Circulations, Acad. Press 1981.
5. M. A. Alaka, The Airflow over Mountains, World Meteorological Organization, Technical Note No. 34 (1960).
6. D. R. Durran, The Effect of Moisture on Mountain Lee Waves, Thesis MIT 1981, NCAR Document CT-65.
7. D. R. Durran, The Effect of Moisture on Trapped Mountain Lee Waves, J. Atmos. Sc., 39, 2490 (1982).
8. R. S. Scorer, Theory of Waves in Lee of Mountains, Quart. J. Roy. Meteor. Soc., 75, 41 (1949).
9. F. M. Ralph, M. Crochet and S. V. Vekatesvaran, Clear Air Doppler Radar Observations of Trapped Lee Waves, Fifth Conference on Mountain Meteorology, Boulder, Colorado 1990, p. 70.
10. J. S. Sawyer, Gravity Waves in the Atmosphere as a Three Dimensional Problem, Quart. J. Roy. Meteor. Soc. 88, 412 (1962).
11. M. Xue and A. J. Thorpe, A Numerical Study of Dry and Moist Lee Waves based on Real Soundings, Fifth Conference on Mountain Meteorology, Boulder, Colorado 1990, p. 60.
12. 77 Av. Denfert-Rochereau, 75014 Paris, France.
13. B. Benech et al., Un Dispositif Experimental Utilisant des Ballons Plafonnants pour l'Etude de la Couche Limite Atmospherique, Adv. Space Res. 7, 77 (1987).
14. R. B. Smith, The Generation of Lee Waves by the Blue Ridge, J. Atm. Sc. 33, 507 (1976).