Active Turbulent Layer Downwind of Mountain Ridges

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Summary

Three types of stationary waves are described. The maintenance of the most powerful one—the lee wave—is thought to be the system of vortex pairs, which are periodically released by the mountain ridge. This system, called "active turbulent layer" (ATL), induces in the airflow wave-like deformations and special turbulence, wind and pressure distribution throughout the lee area.

The dependence of the dimensions and intensity of the ATL on both topographical and meteorological conditions is discussed. Some effects on transient aircraft are shown.

1. Introduction

The intention to search for the cause of the lee wave has led in the period 1946 to 1949 to the definition of four various airflow types: the laminar, standing eddy, wave and rotor streaming. The importance of the disturbed layer as a primary factor for these types of airflow has been emphasized. The dependence of the airflow type on the relative height of the wind layer has been shown.

Initially the study was based mainly on soaring experience alone which consists of about 100 flying hours under lee wave conditions downwind of various ridges. After simultaneous evaluation of appropriate synoptical data and by comparison of the results with various theoretical treatments (Küttner, Lyra, Queney, Scorer) there remain some observed details in airflow structure lacking a theoretical explanation. One of the most impressive examples to be mentioned is the sudden catching of the sailplane by the rotor cloud as the latter jumps quickly against the wind direction.

Written discussion on the question with Karl Erik Övgard and since 1949 with Dr. R. S. Scorer have been of great importance for my further work. Also the invitations to the 4th OSTIV Congress at Madrid 1952 and to the Discussion Meeting on Airflow over Mountains arranged by the Royal Meteorological Society at London 1955 supported me greatly in my work.

During the last few years main attention has been drawn to the stationary wave streaming, which has led to the distinguishing of three wave types with different airflow conditions: Inversion wave, lee wave and composite wave.

The inversion wave (Fig. 1) represents the discontinuity surface deformation caused by the effect of a mountain ridge on the structure of the layer of air below the inversion. Throughout this ground layer there may occur both unstable or stable temperature stratification but mostly light winds only. The inversion layer is often associated with a marked wind shear. With suitable air humidity near the inversion this wave type supports the development of stationary wave clouds in the area of the most distinct wave crest, which clouds are stationary without any systematical movements almost just above the mountain ridge (Photo 2 a). The aspect ratio of these lenticular clouds is usually small. They form no trains, but may occur in several separate formations, each above the other (Photo 2 b). No turbulence of importance is to be expected in the space effected by the inversion wave.

The observations suggest that the lee waves (Fig. 3) correspond to an internal wave system spreading out from the disturbed layer of special structure, which is maintained in action through periodical release of vortex pairs from the mountain ridge. Older vortex pairs are moving through the lee area and initiate long wave trains, affecting the air space far beyond the obstacle. The occurrence of lee waves is connected with stable lapse rate and with a deep layer of sufficient wind velocity and suitable wind direction. Because of the striking regularity of the vortex system, resembling the known Kármán vortex street, the directly affected part of the wind layer is called the "active turbulent layer" (ATL).

The corresponding wave clouds are of great aspect ratio (Photo 4) and form trains reaching sometimes hundreds of kilometers away from the mountain ridge, as has been shown e. g. by Desmond and Radok. The first wave crest is located directly over the lee area usually at a distance equal to about tenfold the height of the ridge. Wave and rotor clouds are subjected to small periodical changes of position. Heavy turbulence appears in limited parts of the ATL. The details will be described in the following part of this contribution.

The third stationary wave type is the composite wave (Fig. 5), representing the combination of both the above described wave types. The structure of the lower airflow layer corresponds to the ATL, but higher levels approach more to the inversion wave. The wave clouds of the first lee wave are tilted toward the mountain ridge in higher levels (Photo 6). The gustiness and strength of vertical wind components is usually weaker when compared with the pure lee wave. The train of wave clouds is limited to the space near the obstacle if it appears at all.

As a deformed lee wave one must mention rotor streaming, which develops when the height of the wind layer is limited (Fig. 7). The vortex pairs of the ATL are then squeezed in very low layer and have lost the possibility of maintaining stable rotation except in the area close to the mountain ridge. Rough gustiness and vertical airdrafts in connection with

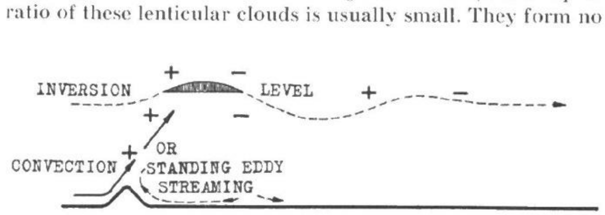

Fig. 1: Scheme of inversion wave

Photo 2 a: Example of inversion wave clouds   By L. Larsson

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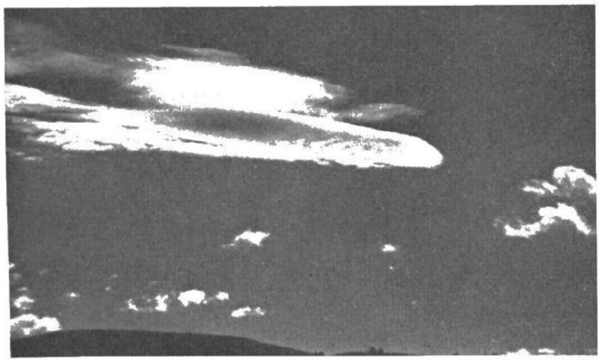

Photo 2 b: Inversion wave over Giant Mountains on May 31, 1955, at 0735 local time
By M. Koldovsky

large local pressure fluctuations appear in the affected space. Suitable humidity supports the development of a single vigorous roll cloud, which remains stationary at a shorter distance from the mountain crest than that corresponding to the usual wave length (Photo 8 a). Another humidity distribution may change completely the cloud appearance although the airflow conditions remain without any variation (Photo 8 b). The leading edges of both clouds reveal sudden jumps against the wind repeated in periods of a few minutes.

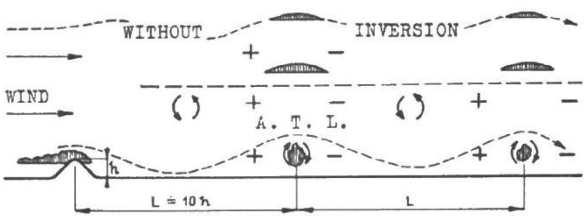

Fig. 3: Scheme of lee wave

The periodical fluctuations of rotor and wave clouds in a limited space are designed in Fig. 9. Photographs 10 a, b represent, respectively, examples of the wave cloud in its border positions before and six minutes after the jump against the wind.

All the mentioned features of rotor streaming may be experienced in clear air or inside a thick cloud layer depending on the humidity conditions.

In a further study the main attention was drawn to the system of the turbulent layer responsible for both the lee wave and rotor streaming.

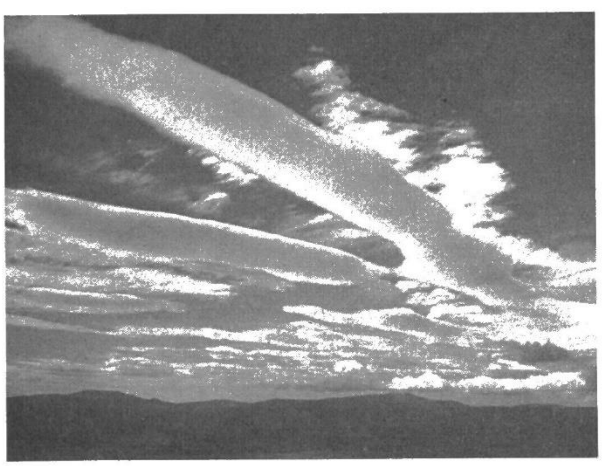

Photo 4: Example of lee wave clouds south of the High Tatra crest
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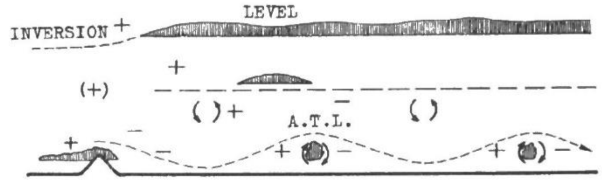

Fig. 5: Scheme of composite wave

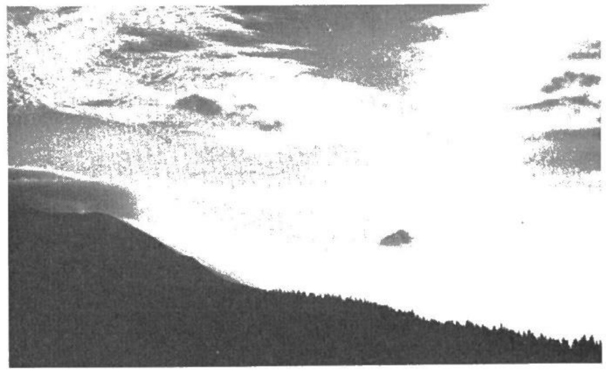

Photo 6: Example of composite wave cloudiness. Note leading edge of high lenticular cloud tilting toward the mountain crest which is hidden in the cap cloud. The appropriate rotor cloud is outside of this photograph to the right
By Dr. A. Becvár

The phenomenon has been considered as a problem of either macroaerodynamical or microsynoptical scale, with both studies coinciding in its solution. The model of empirical study is represented here by the mountain ridge, free airflow across the "model" represents the function of an aerodynamical tunnel, depending on the actual synoptical situation. The observations are made inside the affected space on the ground as well as in the air.

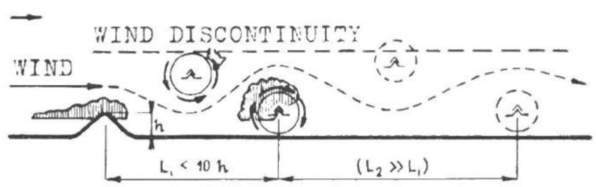

Fig. 7: Scheme of rotor streaming

2. *Active turbulent layer*

The empirical solution is represented by the active turbulent layer established and maintained in the lee area by periodical release of stable vortex pairs from the mountain ridge. The empirical base for the conception of the active turbulent

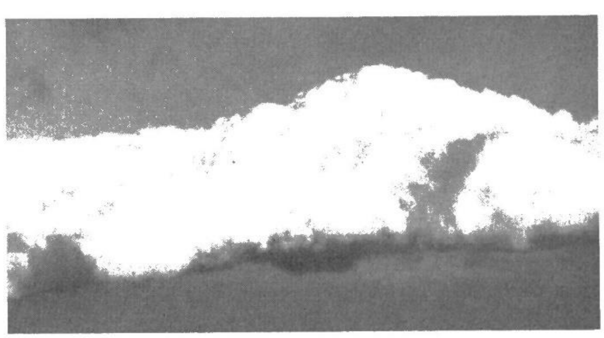

Photo 8 a: Typical rotor cloud, the main feature of the rotor streaming, which usually appears in a single row relatively close to the mountain ridge
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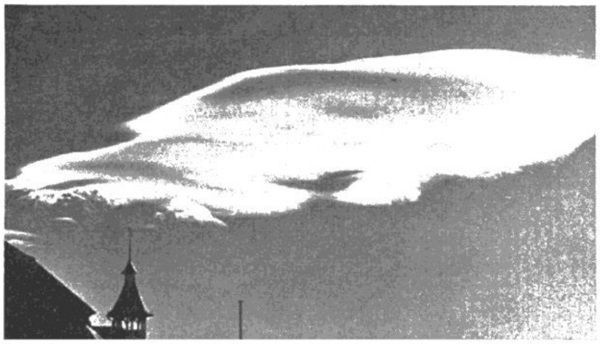

Photo 8 b: Another quasistationary cloud type which appears during rotor streaming conditions. The cloud as a whole remains in the same area but its shape is changing in short periods. The changed humidity distribution is the cause of a completely different cloud appearance compared with the preceding photograph By D. A. Becvár

layer (ATL) has been established by systematical flight observations, made by crews of planes crossing a salient mountain ridge of the height h = 400 m as well as by the experience of glider pilots, flying in the lee waves in the same region. With suitable wind and stability conditions (mostly during winter months) more than 50 traverses of the lee space were made together with supplementary ground observations and upper wind measurements from the nearby airfield.

During the landings in most of the mentioned cases significant altimeter errors were observed reaching in a few extreme cases the value of 100 ft between the beginning and the end of the runway. This is believed to be the manifestation of local pressure differences of dynamical origin that affect the lee space when the ATL is acting.

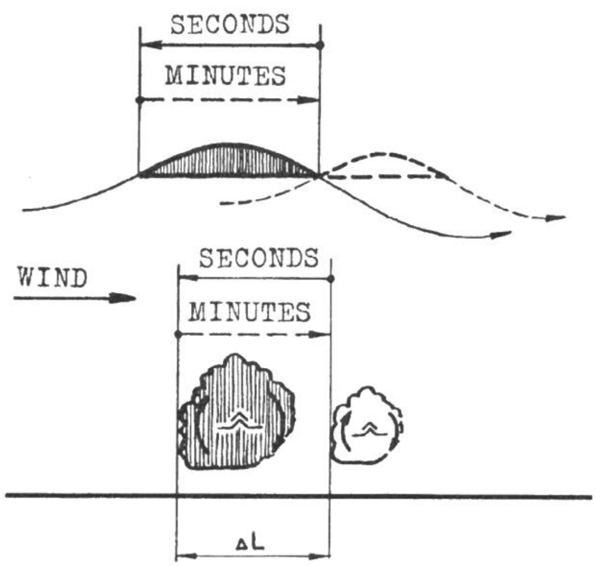

Fig. 9: Scheme of periodical position changes of rotor and wave clouds during the lee wave or rotor streaming

All traverses made in levels a, b, c (Fig. 11) confirm the existence of two separate layers (a, c) with heavy gustiness concentrated in isolated centers, weakening gradually with a distance from the ridge. The traverses in the level b have shown a thin layer with laminar airflow conditions and with alternate up- and downdrafts. When flying against the wind in the level b an unusual decrease of ground speed will often be reported. This corresponds to an increased horizontal wind component, as shown for the level b by the upper wind measurements.

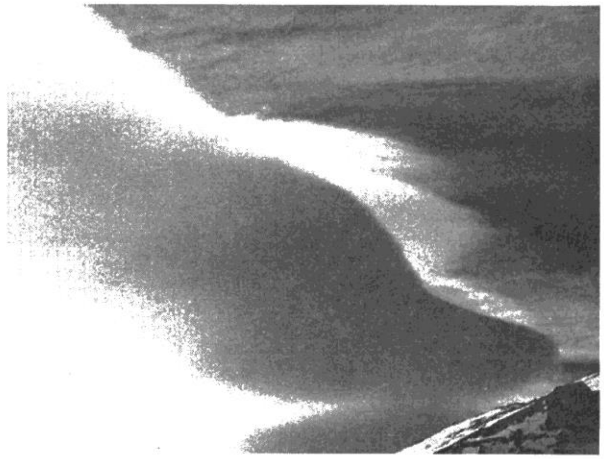

Photo 10 a: Wave cloud south of High Tatra mountain in its rear position—before a leap against the wind blowing from the right By Dr. A. Becvár

The nature of the upper gustiness centers is shown by down- and updrafts experienced just in front and downwind of the upper vortices, which is the opposite of the known "ground rotors". The theory of vortex pairs appearing in aerodynamics shows the inability of such formations to remain stable in a horizontal airstream with axis plane parallel or perpendicular to the undisturbed airstream. But some inclined axis plane may provide stability for a vortex pair that becomes able to affect greatly the surrounding airflow. The theory of an ATL based on this assumption supposes the formation of windward and lee vortices leaving periodically the space of mountain ridge in the form of stable vortex pairs with inclined axis plane (Fig. 12).

From the moment of release each vortex pair is maintained by inertia and usually undergoes two stages continuously alternating: moving and standing stage. Both stages have the same duration of a few minutes, which time depends on the period of the release of the following vortex pairs. This period has been observed to be shorter with smaller obstacles and stronger winds. For mountain ridges about 1000 m high it is of the order of tens of minutes.

The lee vortices of each vortex pair follow, during their moving and standing stages, the ground drift path, while the upper ones are drifting through the upper path. In this way two distinct layers of gustiness are formed separated by a

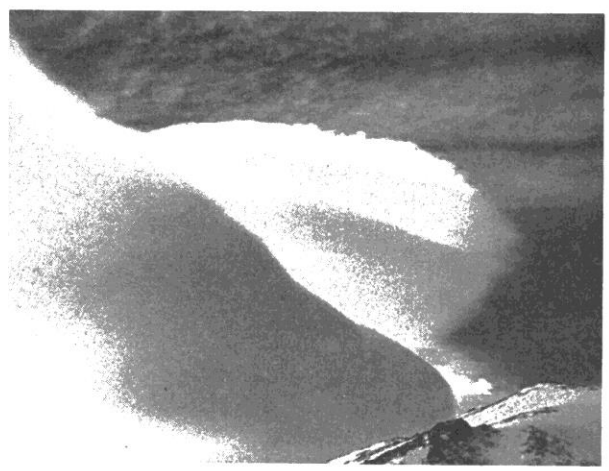

Photo 10 b: Wave cloud south of High Tatra mountain six minutes later in its front position By Dr. A. Becvár

Photo 15: Lee vortex during its standing stage in the form of a rotor cloud. This photograph was taken in the area of the preceding two photos on another occasion with increased air humidity but with similar airflow conditions
By M. Koldovsky

sible for further airflow deformations corresponding to the composite wave type. In this way the ATL system could explain the measured upper wind distribution with local maximum around the level 2 h, the occurrence of heavy clear air turbulence centers registered round the level 3 h, as well as the local pressure and wind fluctuations throughout the turbulent layer. The intensity of all these mentioned features may reach such extremes as observed in the area of Sierra Nevada.

In special cases there occur strong wind layers of sharp limited vertical extent, corresponding to 4 h—2 h even in the lee of medium and low ridges. Under these conditions an ATL of the same structure but smaller dimensions is observed, with very significant local pressure deviations between the wave troughs and crests. This type of airflow is known as the "rotor streaming".

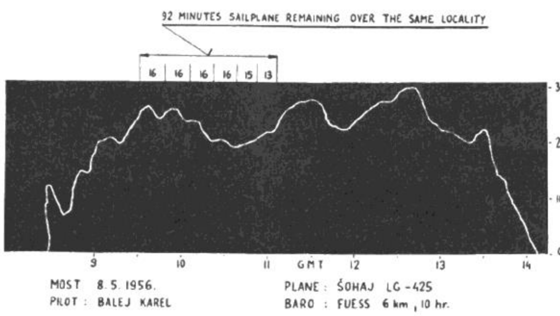

Fig. 16: Barogram of a soaring flight during lee wave conditions south-east of Ore Mountains. The denotated part contains six fluctuations experienced by the pilot tending to remain stationary to the ground. Indicated air speed fluctuations of similar periods were also reported

3. *The ATL effects*

Very deep wind layers will support the vertical propagation of lee waves induced in the airflow by the ATL. Thus the secondary thermodynamical effects well expressed in the area of wave crests and wave troughs may partially eliminate the local pressure deviations caused by the mechanism of the ATL. This elimination becomes insignificant with shallow wind layers. Then even in lee of low ridges there occur pressure differences of the order of several millibars between locations only a few kilometers apart.

The complexity of the ATL under similar conditions may lead to serious navigational errors during a horizontal flight and, what is even more important, during instrument approach-to-land. Fig. 18 represents the enlarged sector of Fig. 12 with isobaric surface deviations corresponding to $\pm \Delta p$. The plane flying downwind through the area with sufficient engine power to eliminate the effect of downcurrents will follow the undulating isobaric surface without experiencing any change of pressure altimeter and variometer indications.

Usually full engine power cannot overcome the strong downcurrents and the altitude indication decreases in the space of increasing positive altimeter error. The resulting pressure altimeter readings underestimate the true altitude in critical points of the flight path. The reverse will appear when flying in opposite direction—the altitude indication will decrease with increasing negative altimeter error. The result is the addition of both indicated height difference $-\Delta H$ and the unknown height difference corresponding to $-\Delta p$. The sum of these two differences will exceed the order of 100 m even in lee of low mountains.

Owing to longer traverses of the downcurrent area when flying with headwind the forced height difference $-\Delta H$ will be greater than in the opposite case. It may be enlarged many

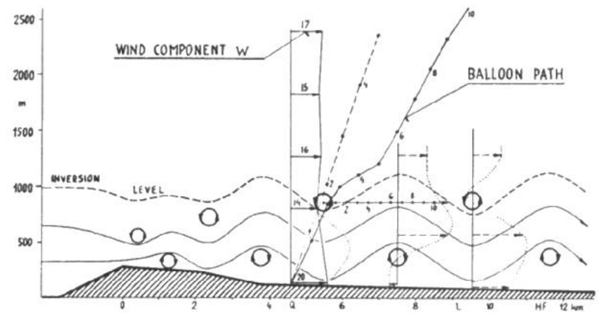

Fig. 17: The scheme of possible turbulent layer mechanisms responsible for unusual pressure and wind fluctuations, registered by two stations at Malta and described by Lamb. The dots on the path of a radiosonde balloon released from a third station represent positions at minute intervals after release (1—10). Corresponding upper vortex positions denoted on the horizontal axis may explain the measured decrease of the vertical velocity between the second and fifth minutes of the ascent.

times when crossing the unfavourable area with a small angle — during the flight almost parallel to the mountain ridge. This case will correspond on many airfields in hilly countries to final approach track directions.

The same will take place if the descending flight ABCDE is intended (Fig. 18). The true flight path with eliminated downdraft effect will be $AB_1\,CD_1\,E$ with changed rate of descent without indication. The forced altitude decrease will cause further flight path deviation corresponding to the dotted line $AB_1\,C_2\,D_2\,E$, which contains the critical point D_2.

4. *Conclusion*

The known lee wave and rotor streaming cases, occuring in the area of low as well as high mountains under appropriate airflow conditions, lead to the result that the causes of these similar airflow types must be similar, too. It has been shown that the ATL could represent the system occuring in various

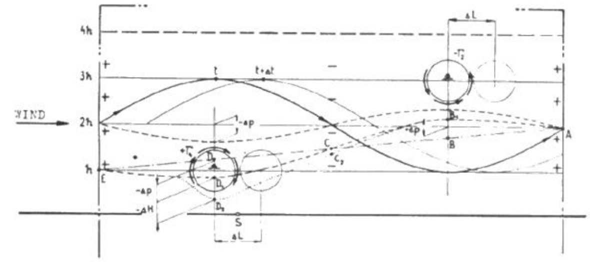

Fig. 18: The enlarged section of Figure 7 with denoted front and rear positions of two included vortices (heavy and light circles) and with appropriate streamline deformation. The broken line with opposite wave deformation means the isobaric surface corresponding to the level 2 h. The deviations $\pm \Delta p$ are the result of aerodynamical forces caused by both vortices during their standing stage. The line ABCDE means an intended descending flight level in upwind direction. Owing to pressure altimeter and variometer errors the real flight path will be AB_1CD_1E. If the engine power will not overcome the effect of strong downdraft, then the resulting flight path will correspond to the dotted line containing the critical point D_2

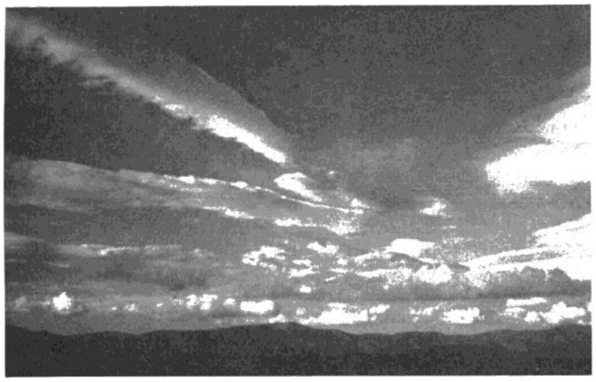

Photo 19 a, b: Quickly changing cloud appearance downwind of High Tatra before the quasistationary ATL system is established. Only one minute time difference between these photos shows clearly the sudden increase in cloud amount as well as cloud position changes By Dr. A. Becvár

dimensions and intensities, depending on orographical as well as meteorological conditions.

The unchangeable topography of any locality and the continuously varying meteorological conditions represent an unlimited number of cases differing by airflow structure, by cloud appearance or by both. In the above paper the airflow structure alone has been chosen as a satisfactory criterion in order to distinguish different airflow types. It has been shown that a different humidity distribution with height may completely change the external appearance of clouds even during the same airflow type.

Among the main airflow types the lee wave and the rotor streaming only have been found to depend on the development of an ATL. This may explain why the lee waves and rotors are generally short time phenomena and how many other types may occasionally become similar, when judged only on the basis of cloud appearance.

The local airflow conditions may change rapidly for hours when approaching to the state supporting the full development of an ATL (Photo 19 a and b). The duration of really ideal conditions, represented by photograph 4, may be limited to periods of a few hours only. For that reason these rare ideal periods deserve the topmost attention of the observer.

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