OBSERVATIONS OF MOUNTAIN-INDUCED ROTORS AND RELATED HYPOTHESES: A REVIEW

Joachim Kuettner[1*] and Rolf F. Hertenstein[2]

[1]NCAR, Boulder, Colorado
[2]Colorado Research Associates division of NWRA, Boulder, Colorado

1. Introduction

By the 1920s and 30s, glider pilots had learned to soar in the convective boundary layer, which was always slightly turbulent. On a day in 1933 when they discovered the mountain wave and its surprisingly smooth flow they also discovered that the convective boundary layer underneath had changed to hazardous turbulence. In this way they not only discovered the lee wave and the rotor flow, but also their unholy marriage which seems "undivorcable".

With the advent of high-altitude commercial aircraft, the upper-level mountain wave attracted most of the attention of the scientific community, while the low-level rotor earned only the respect of the general aviation community. Accordingly, the number of scientific papers devoted to mountain waves vs. rotors has a ratio of approximately 40:1. A group of MAP scientists is now trying to improve this ratio and give the rotor phenomenon its deserved attention.

2. Field Investigations of Rotors

Actually the rotor cloud had already been discovered by the well known dynamicist H. Koschmieder in 1920, who photographed it and made a thorough analysis of his accidental observation. He estimated the vertical motion on the leading edge of what he called the "Wolken-Walze" (cloud roller) at + 10 ms^{-1}.

It fell upon the always curious glider pilots to further explore these phenomena and, due to their cooperation, it was possible to determine the wave nature of the observed vertical motion field overlying the lower, turbulent rotor flow (Kuettner, 1938, 1939). A widespread opinion of glider pilots at that time held that the rotor flow may play a primary role in the development of mountain waves, often providing - as they observed - a larger obstacle to the flow than the mountain itself. This (unfunded) exploration phase did not involve an organized field campaign and before one could be organized, WW II interfered. It was more than a decade later that this research was continued in the USA in a well prepared three-year field project.

The "Sierra Wave Project" (SWP) was primarily devoted to the study (observational and theoretical) of the mountain wave. However, at the initiative of Jaques Bjerknes, J. Knox (UCLA) undertook a ground-based study of the rotor phenomenon and its possible relation to a hydraulic jump. The surface convergence lines in the wind field were tracked by mobile weather stations, as were the movements of the leading edge of the rotor clouds.

However, it was not until three years later that the destruction of a sturdy sailplane from the Jet Stream Project (JSP) by a huge rotor raised wide interest in the scientific and aviation communities, stimulating a series of interpretive studies of the rotor phenomenon (Queney 1955; Long 1955; Scorer and Klieforth 1955; Förchtgott 1958; Kuettner 1959). They are briefly discussed in Section 4. The JSP used B-29 and B-47 aircraft, in addition to gliders, to study the mesoscale features of the mountain wave. The B-29 research aircraft penetrated rotors near the 500 mb level. What was encountered is described in Section 3.

In Europe in the late 1950s, several French field campaigns investigated the mountain waves and rotors in the French Alps and their connection with the Mistral (Gerbier and Berenger, 1961). Earlier, based on careful observation of mountain waves and rotors in Czechoslovakia, Förchtgott (1949) described vortex street-like series of rotors forming beneath trapped waves.

The next field investigation, the Colorado Lee Wave Observational Project (Kuettner and Lilly, 1968), took place in the Boulder area of the Rocky Mountains in the late 1960s and early 1970s and is best known for its case study of the 11th January, 1972 windstorm by multiple research aircraft (Lilly and Zipser, 1972). The flight data show enormous amplitudes of high-altitude wave activity, severe high- and low-altitude turbulence and intense surface winds. Much later these findings were successfully simulated by a series of high-resolution numerical models (Doyle, et al., 2000). The Colorado campaign led to a special investigation of the rotor phenomenon and low-level turbulence zones by Lester and Fingerhut (1974). They confirmed the existence of two basic rotor types, including the powerful hydraulic-jump type (Fig. 1), our Type 2 (see Section 3).

It appears that in the following 25 years, interest in the rotor phenomenon vanished in spite of several cases of aircraft disasters, suspected or proven to be caused by rotors. In connection with the MAP project, interest in the rotor phenomenon was rekindled. This led to a fundamental paper by Doyle and Durran (2002), who successfully simulated the rotor formation under trapped lee waves.

* *Corresponding author address*: Joachim Kuettner, UCAR, PO Box 3000, Boulder, CO 80307

We have now formed an international study group that is planning a Rotor Project to be conducted in the years 2003 to 2005, in the same area as the SWP. While making use of the SWP data, the project intends to introduce advanced observing systems such as dual-Doppler Lidar, K-band radar, a surface-station network and modern research aircraft to probe the total rotor/wave system. We will hold an informal planning meeting during the AMS conference.

3. Observed Characteristics of Rotors.

Very little is known about the internal structure of rotors. With the few exceptions of rotor penetration by fully instrumented aircraft, existing observations are more of the anecdotal type from involuntary encounters. Practically every pilot agrees that rotors are among the most turbulent and dangerous phenomena of the atmosphere, rivaling even thunderstorms.

It was during the 1955 Jet Stream Project that the B-29 jetstream aircraft penetrated a powerful rotor near the 500 mb level. The flight data (Fig. 2) show approximately 20 positive and negative peak gusts in less than one minute flight time, reaching values as high as +/- 20 to 25 ms^{-1}. This suggests internal eddy sizes on the order of decameters, similar to those observed on another day in which a powerful rotor destroyed the aforementioned research glider. Eddies of this small size are not resolved at present by numerical simulations of mountain-wave systems.

This type rotor, which we call Type 2, is fortunately rare, and is probably responsible for several air disasters. It should be distinguished from the more common Type 1 rotor, which is frequently recognizable by mountain-parallel fracto-cumulus lines, though it can be cloudless. They often mark the wave crests of overlying trapped mountain waves, a welcome visual aide to glider pilots on wave soaring adventures, and a warning of potentially hazardous turbulence to other alert pilots.

Of primary interest is the Type 2 rotor, not only because of its danger to aviation, but because it seems to be a substantially different phenomenon than Type 1, and to have many of the characteristics of a hydraulic jump (Kuettner, 1959; Lester and Fingerhut, 1974). It usually has a massive roll cloud with nearly vertical leading edge, and its footprint is different: as the aforementioned work by Knox (1952) showed, these rotors don't follow the various bends in a mountain range, but form a straight barrier extending crosswind the full length of the mountain range (Figs. 3,4). They also may reach heights of 25,000 to 30,000 ft, exceeding considerably the cap cloud deck over the mountain range.

If the cap cloud is deep, a large "cloud-water fall" forms, indicating that the cold upstream air mass rushes down the mountain lee slope, where it impacts and erodes the stagnating air mass in the leeside valley. This increases the effective depth of the mountain slope and may cause hurricane-force surface winds between the mountain range and the far-downstream rotor, carrying dust storms into the rotor cloud. Diurnal effects observed during the SWP may intensify the rotor. The so-called "4 o'clock wave" became well known among pilots of the SWP when rotor intensity reached a maximum. This was confirmed by the ground observations that showed the surface potential temperature rising by 2 K from the foot of the mountain to the foot of the rotor (Fig. 5).

In our opinion it is unlikely that aircraft can be designed strong enough to withstand the excessive loads of a fully developed Type 2 rotor. (The sailplane destroyed in the leading edge of the rotor during the JSP was designed for 8-10 g, but suffered approximately 16 g according to the evaluation team.) This rare type rotor should be avoided the same way boats avoid Niagara Falls. It will be one of the tasks of the planned Rotor Project to establish the criteria for its formation, thus leading to new forecast tools.

4. Theories and Hypotheses

Following the discovery of the mountain wave and the first descriptions of the rotor phenomenon, Kuettner (1939) argued that the observed wind shear on the top of the leeside stagnating boundary layer causes the observed rotor circulation, following the Bjerknes, et al. (1933) shear-instability theorem. Lyra (1943), proposed that the wave pressure field causes secondary circulations in the surface layer, due to boundary layer separation ("Grenzschicht-Ablösung"). This may still be a valid hypothesis for Type 1 rotors, especially under trapped waves. Queney (1955) advanced his so-called "cat's eye" theory, which derives rotor-like circulations in shear flow around levels of zero wind velocity in the undisturbed current (essentially a kinematic theory).

Long (1955), in his laboratory and theoretical work, treated stratified fluids without vertical wind shear, and reproduced a rotor-like stagnating air mass in the general position where the rotor is found. He called it a "turbulent eddy". Scorer and Klieforth (1959) developed a theory of large amplitude mountain waves, showing that eddies containing reversed flow form first at the level at which mountain waves reach their steepest slopes (essentially a theory of wave breaking). Kuettner (1959) proposed a hydraulic-jump theory with reduced gravity upper boundary, which produced a powerful hydraulic jump, whose height exceeded that of the upstream cap cloud when surface heating was added, as observed in the SWP (see Fig. 6).

Recently attention has focused on the 3D aspects of rotors (Gheusi et al., 2000; Clark et al., 2000) which are of special interest as they may produce the dangerous "subrotors" of decameters size that seem to present the highest hazards to aviation inside and in the leading edge of Type 2 rotors.

Following Doyle and Durran (2002), who successfully simulated rotor development in trapped mountain waves and its intensification by surface heating, we will attempt, in the following paper, to 1) determine the conditions under which Type 1 vs. Type 2 rotors form, 2) investigate the question of "wave-induced rotors" vs. "rotor-induced waves" and 3) study the effect of a secondary mountain range, such as the Inyo Mountains in the lee of the Sierra Nevada Mountains.

5. Future Research

What direction should future research take to fill the gaps in our understanding of the rotor phenomenon?

On the observational side, our ignorance about the internal fine structure of the rotor should be removed by applying the most advanced remote-sensing techniques. Also, a climatological study of the conditions leading to rotor formation in general is needed to improve our understanding, and the prediction of rotor events. On the scientific side, more attention should be given to the role of moisture in the formation and energy level of rotors. For example, the part played by the so-called "cloud waterfall" and its evaporative intensification of the downslope winds should be better understood. In addition we should include the investigation of the energy supply imparted to the rotor itself by cloud formation, both through its base and its leading edge. Finally, the serious flight hazards of the rotor phenomenon may justify 3D simulations with grid spacing down to 10 m, because it is on this scale that the destructive forces exist that damage or destroy aircraft and injure their occupants.

6. References.

Clark, T.L., W.D. Hall, R.M. Kerr, D. Middleton, L. Radke, F.M. Ralph, P.J. Neiman and D. Levinson, 2000: Origins of aircraft-damaging clear-air turbulence during the 9 December 1992 Colorado downslope windstorm: numerical simulations and comparison with observations. *J. Atmos. Sci*., **57**, 1105-1131.

Doyle, J.D. , D.R. Durran, B.A. Colle, C. Chen, M.Georgelin, V. Grubisic, W.R. Hsu, C.Y. Huang, D. Landau, Y.L. Lin, G.S. Poulos, W.Y. Sun, D.B. Weber, M.G. Wurtele and M. Xue, 2000: An intercomparison of model predicted wave breaking for the 11 Janurary 1972 Boulder windstorm. *Mon. Wea. Rev*., **128**, 901-914.

Doyle, J.D. and D.R. Durran, 2002: The dynamics of mountain-wave induced rotors. *J. Atmos. Sci*., **59**, 186-201.

Förchtgott, J., 1949: Wave streaming in the lee of mountain ridges. *Bull. Meteor. Czech*., **3**, 49pp.

Gerbier, N. and M. Berenger, 1961: Experimental studies of lee waves in the French Alps. *Quart. J. Roy. Meteor. Soc.,* **87**, 13-23.

Gheusi, F.J., J. Stein and O. Eiff, 2000: A numerical study of three dimensional orographic gravity wave breaking observed in a hydraulic tank. *J. Fluid Mech*., **410**, 67-99.

Knox, J., 1952: A preliminary report on hydraulic pressure jumps as observed with the Sierra Wave. Univ. of Calif., Meteor. Dept.

Kuettner, J.P., 1938: Moazagotl und Föhnwelle. *Beitr. Phys. Frei Atmos*., **25**, 79-114.

Kuettner, J.P., 1939: Zur Entstehung der Föhnwelle. *Beitr. Phys. Frei Atmos*., **25**, 251-299.

Kuettner, J.P., 1959: Rotor flow in the lee of mountains. GRD Research Notes, No. 6, Air Force Cambridge Research Centre. 20 pp.

Kuettner, J.P. and D.K. Lilly, 1968: Lee waves in the Colorado Rockies. *Weatherwise*, **21**, 180-185.

Lester, P.F. and W.A. Fingerhut, 1974: Lower turbulent zones associated with mountain lee waves. *J. Appl. Meteor*., **13**, 54-61.

Lilly, D.K. and E.J. Zipser, 1972: The front range windstorm of 11 January 1972 - a meteorological narrative. Weatherwise, **25**, No. 2, 56-63.

Long, R.R., 1955: Some aspects of the flow of stratified fluids. III. Continuous density gradients, *Tellus*, **7**, 342-357.

Lyra, G., 1943: Theorie der stationären Leewellenströmung in freier Atmosphäre. *Z. angew. Math. Mech*., **23**, 1-28.

Queney, P., 1955: Rotor phenomena in the lee of mountains. *Tellus,* **7**, 367-371.

Scorer, R.S. and H. Klieforth, 1959: Theory of mountain waves of large amplitude. *Quart. J. Roy. Meteor. Soc*., 85, 131-143.

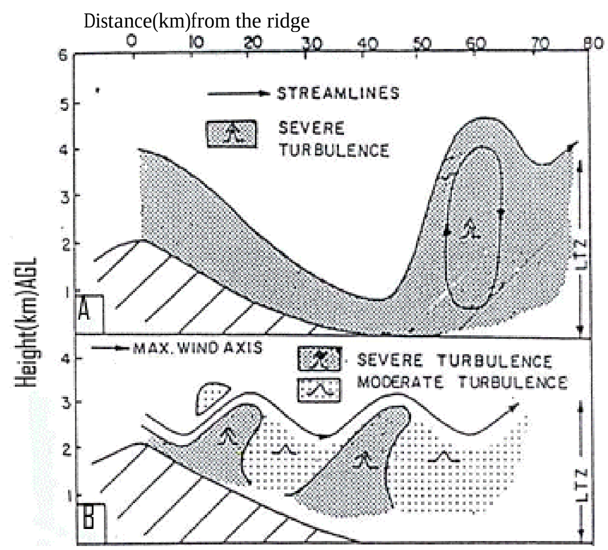
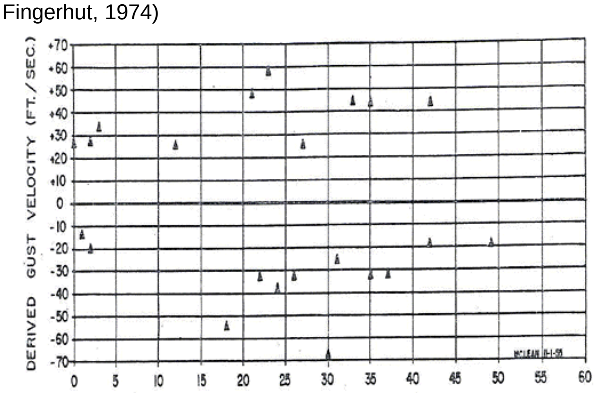


Figure 1. Schematic of A) Type 2 rotor, and B) Type 1 rotor. LTZ indicates Low-level Turbulent Zone. (After Lester and Fingerhut, 1974)



B-29 Bishop, CA. 1- Apr, 1955 (1322-23 pst) 17,200-17,700 ft

Figure 2. Vertical gust velocities measured while penetrating a Type 2 rotor.

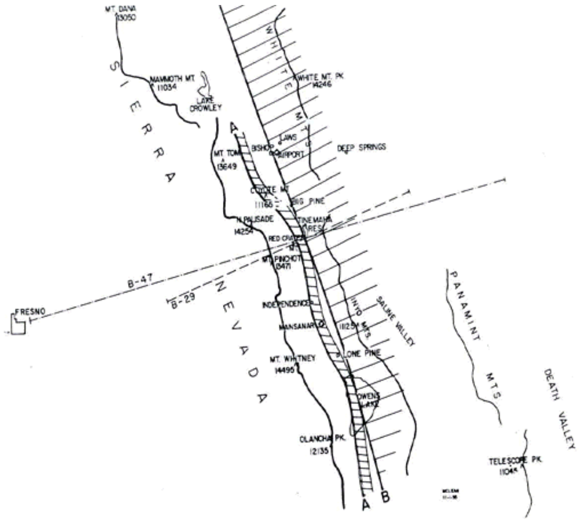


Figure 3. Normal (Type 1) rotor cloud (Line A) compared to severe (Type 2) rotor cloud (Line B) in the lee of the Sierra Nevada Mountains.

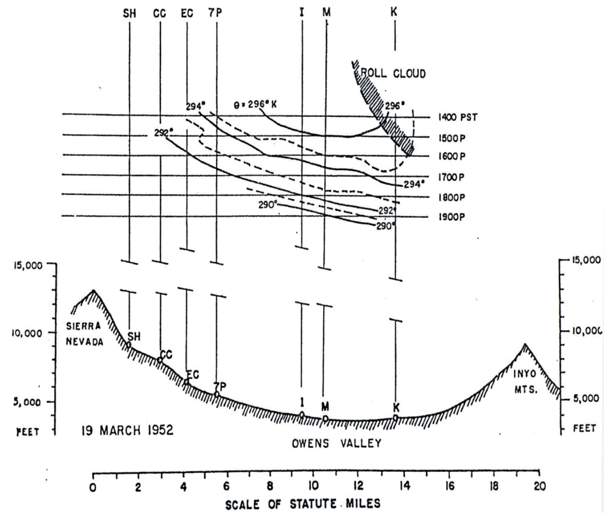


Figure 5. Potential temperature field and roll cloud position as a function of time (upper part) measured by a mobile weather station over the Owens Valley (lower part).

Figure 4. Type 2 rotor (cf. Fig. 3) and overlying lenticular clouds extending in a straight line for 150 km parallel to the Sierra Nevada Mountains.

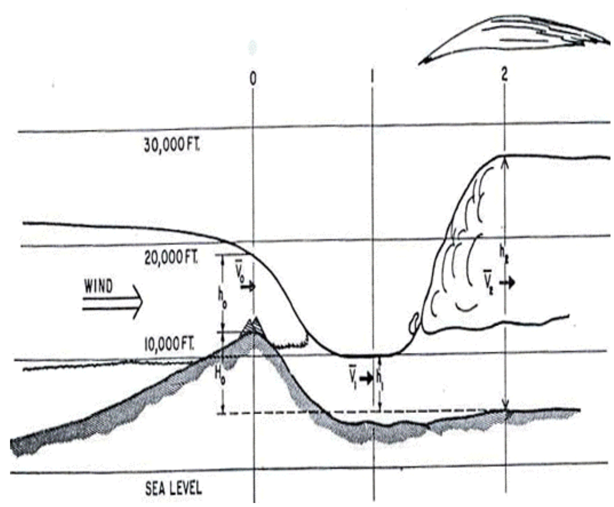


Figure 6. Schematic diagram of hydraulic air flow over a mountain range. Note the height of the rotor cloud exceeding that of the cap cloud.