Lee waves in the Andes Region, Mountain Wave Project (MWP) of OSTIV

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Abstract

Frequent occurrence of strong cross-mountain winds makes the Argentinean Andes a unique location to investigate lee wave systems and use them for long distance soaring flight. Results from the 1999 Andes Expedition of the Mountain Wave Project (MWP) confirmed the potential for excellent soaring with straight out flights up to 1550km. Analyses of data collected in airborne measurements from a motorglider yield a surprisingly high vertical momentum transport and indicate wave motion more than 100km downstream of the mountains.

Preparations and goals

In 1998, a small group of meteorologists, physicists, engineers and pilots, all members of OSTIV, started to gather knowledge about meteorological conditions in the Argentinean Andes to improve soaring meteorology and to investigate the feasibility of further lee wave and rotor research in this area. To this end, they founded the Mountain Wave Project (MWP). Until that time, only occasional flying activities and little atmospheric research had been reported from that region. Klaus Ohlmann was the first to explore the central part of the Argentinean Andes in December 1998 and January 1999. He discovered a great potential for soaring flight in the extensive lee wave systems of that area. The first flights included distances of more than 1000 km. Previously, reports on mountain waves came mostly from commercial airline pilots and from observers on the ground.

The MWP team planned their first research and flying expedition for the period November/December 1999. A climatological study[1] showed the statistical probability of strong upper-level westerly winds and the reliable existence of lee waves. Based on these studies, it was decided to use the aerodrome of San Martin de Los Andes (40°S, 70°W, Fig. 1). A more northerly airport (for example Mendoza) closer to higher mountains (Aconcagua, about 7000 m MSL) was discarded, because this region lacks the high frequency of strong winds compared to the location 500km further south. Also, the farther south, the more frequently cold fronts from the SW penetrate to the east of the Andes, improving wave development through prefrontal wind acceleration. It is also a common observation that waves in the lee of high mountains rarely reach down to levels that are easily accessible by a short aerotow. Motorglider flights in the Himalayas more than a decade earlier encountered similar conditions[1a]**.**

The expedition had two main objectives that combined sport soaring and science:

- To draw the attention of the gliding community to a promising region and explore its potential for setting new world soaring records,
- To improve knowledge of lee waves in the Andes by collecting data through airborne measurements as well as testing and verification of various forecasting methods.

For the period in question, the German Military Weather Service contributed a special mesoscale model output[2]. Additionally, the German Weather Service (Deutsche Wetter Dienst, DWD) collected upper level (radio soundings) and surface data in this area and transmitted these data to the MWP via ftp. The Lester-Harrison nomogram[3] was employed for a simple and quick forecast of the lee waves thereby checking the reliability of this method for the area in question.

Airborne measurements by an instrumented motorglider were planned in order to gather reliable data about lee waves in that region. The research missions were designed to measure the number of wave oscillations downstream of the mountains, vertical momentum transport, vertical extent of waves, and if possible, wind speed and stability requirements for the existence of lee waves. The plan also called for investigating positions of rotor bands, since they are particularly important for flight safety near mountains. Rotor bands are often indicated by cumulus fractus clouds and, thus, mark a favourable soaring flight track more clearly than altocumulus lenticular clouds. (For a basic discussion of rotors see Queney[4], and Doyle and Durran[5]).

Aircraft and instrumentation

The group of scientists and engineers (Rene Heise, Wolf-Dietrich Herold, Martin Just, Carsten Lindemann, Michael Meyn) together with pilot Klaus Ohlmann was fortunate to have been supported generously by Dr. Reiner Stemme of Stemme Aircraft factory in Strausberg (near Berlin), who had a factory owned Stemme S-10 motorglider shipped to Argentina for this research. This motorglider proved to be an optimal research platform. Its excellent gliding performance at high speeds made it possible to maintain indicated airspeeds (IAS) around 180 km/h over long periods in order to cover large distances in the strong winds at altitude. Furthermore, the turbocharged engine allowed powered climbs to altitudes in excess of 8000m.

Support also came from Prof. Juergen Fischer of Freie Universität Berlin, who provided and prepared a classical set of measuring devices for atmospheric investigation:

- 2 temperature systems Vaisala and Brose (PT 100)
- Humicap for relative humidity
- Rosemount REC 1241 for pressure and vertical velocity
- Rosemount 1221 for IAS
- Garmin 100 as GPS
- Honeywell HMR 3000 for heading, pitch, and roll.

Post flight analysis proved that this instrumentation delivered reliable and accurate wind measurements, vital for any momentum transport computation. A FDR data logger of 16 bit with 1 Hz time resolution stored the data on a PCMCIA card. The computation was performed using the IDL software package.

Results

Soaring Flights

Of the many soaring flights achieved, ten covered a distance of more than 1000 km, among them one out-and-return flight over 1430 km (world record) and a straight-line flight over 1550 km to Fireland. These outstanding gliding results were limited only by daylight time and the horizontal extent of lee wave flow, which was often disturbed by passing cold fronts with attendant precipitation, change of wind field, etc.

Flight track data from the GPS flight recorders of the gliders were evaluated using Flightplanner to identify updrafts and downdrafts due to lee wave flow in relation to geographical features.

Meteorology

About ten meteorological research flights with full instrumentation were completed to investigate lee wave and rotor patterns.

The most interesting days explored using the complete set of atmospheric instrumentation were the 2nd and 3rd of December 1999. On the 2nd of December weak winds failed to produce waves near San Martin while slightly stronger winds generated waves 150 km to the south. On the 3rd of December a strong lee wave pattern existed over an area extending more than 500 km in north-south direction. This wave pattern broke down after the passage of a cold front from SW. The Lester-Harrison nomogram predicted average updrafts of less than 2.5m/s (weak) for the 2nd of December and around 4 m/s (moderate to strong) for the 3rd of December.

Figure 2 presents the wind speed and vertical velocity of lee waves 150 km south of San Martin on the 2nd of December. The wavelength was 5.6 km at a mean altitude of about 3200 m. The short wavelength is probably due to relatively low wind speed over the topography. It is easily recognizable in the figure that the updrafts are correlated with low horizontal wind speeds (except for the largest vertical velocity at about x = 35 km) and the downdrafts with large horizontal wind speeds, thus documenting negative vertical momentum transport. The wind direction varied from 245 to 262°.

Figure 3 shows the height/distance and potential temperature/distance profile for the wave flight of December 3rd, clearly displaying an oscillating pattern indicating a wavelength of about 18 km. The aircraft power was set to yield an overall 0.35 m/s sink rate.

Figure 4 gives the vertical velocity for two different altitude ranges. The upper one was flown downwind with smaller space resolution because of high ground speed; the lower one was upwind with small ground speed, due to a headwind of around 60 kts. The waves are tilted upwind, also an indication for negative vertical momentum transport.[5] The tilt can be recognized, if a line is drawn in Fig. 4 from the tops of the updrafts of the lower altitude to the updrafts of the higher altitude.

Figure 5 displays wind direction and wind speed. The quality of the measurements shows by the small degree of variation in direction.

The flight legs to collect data for the determination of the vertical momentum flux were approximately 100 km long. They were flown in a constant attitude mode, i.e. with constant power setting, rather than in a constant altitude mode. The analysis of the vertical momentum transport gave an unexpectedly high value of -90.4 kg/s² for the higher traverse and -86.5 kg/s² for the lower traverse. The mean vertical momentum transport over the whole duration of the measurement was - 0.97 Pa for the upper and -1.02 Pa for the lower ranges and thus much larger in absolute value than most of the measurements previously published. The measurements for the 2nd of December yielded –15.8 kg/s² and –0.275 Pa respectively. Measurements during ALPEX (1982)[6] show a maximum of less than –1.0 Pa and in most cases much less. This pronounced difference between the values for the vertical momentum transport presented here and results published elsewhere surprised the authors. Only additional measurements under similar conditions in the same area would be able to confirm these results, possibly indicating a local phenomenon. More recent measurements by stratospheric balloons over the southern tip of South America and Antarctica also yield lower values[7].

Lee waves and rotors normally coexist with turbulent rotors below the laminar wave flow. Rotors are horizontal vortices, which are often induced by lee waves. They exhibit a pronounced return flow toward the mountains in the lower branch of their circulation. Given specific wind profiles with a low level pressure gradient, rotor flow near the surface can develop without associated lee waves. One case was observed where the low level flow produced a confluence of two streams, each channelled by separate valleys about 20 and 30 km, respectively, upwind of the airport (Figure 6). The updraft at the intersection of the two flows displayed features similar to those of a hydraulic jump. It resembled the conversion of kinetic energy, gained when the flow is squeezed between a downslope and a stable layer above, into potential energy. And it appeared rotor-like in that the formation of the accompanying cloud displayed the dynamics of a turbulent vortex. Moreover, using this updraft with a glider frequently provided a direct transition into the laminar wave flow above.

Conclusions

Due to frequency of appropriate wind fields, lee wave studies can be performed much more frequently in the southern hemisphere than in the northern hemisphere, either in New Zealand or in Argentina.

A motorglider is a good measurement platform for in situ measurements, especially since the determination of wind by onboard heading sensor, GPS, and calibrated airspeed indicator is sufficiently accurate.

Soaring flights in lee-waves over long distances are frequently possible in appropriate regions of the southern hemisphere.

San Martin de los Andes might be used as point of departure for a flight to the central region of the Andes between Mendoza and Santiago de Chile, 600 km to the North. There, waves with larger amplitudes can be expected due to the higher elevation of ridges and peaks (more than 6000m).

The predicted wind field from the German military model (BLM/RBL) was more accurate than the wind field from the Argentinean model, which did not represent satisfactorily the intensity of fronts nor their effect of changing wind fields and static stability on waves.

The Lester-Harrison nomogram provides a useful estimate of lee wave intensity.

The vertical momentum transport was found to be larger than most values previously published.

References

[1]Schwerdtfeger, W. and D. W. Martin, "The Zonal Flow of the Free Atmosphere between 10N and 80S in the South American Sector", *J. Appl. Meteor.*, Vol. 3, 1964, p. 726ff.

[1a]Neininger, B., M. Reinhardt and J. Kuettner: Valley circulations as measured in the Himalaya by instrumented motor glider. Proc. Conf. Sci. Results of ALPEX, Venice; GARP Pub. Ser. No. 27, WMO Geneva, 1986, 501-508.

[2]Prenosil,T., R. Amtmann, H. Derichs, "The global relocatable regional weather prediction model of the German Military Geophysical Office", *Meteorol. Appl.*, Vol. 6, 1999, pp. 159-171.

[3]Lester, P., "An evaluation of a lee wave forecasting nomogramme", *Technical Soaring*, Vol. 3, 1974, p. 110ff.

[4]Queney, et al. "The airflow over mountains", *WMO Technical Note 34*, WMO, Geneva 1960

[5]Doyle, J. and D. Durran, 2004, "Recent developments in the theory of atmospheric rotors", *Bull. Amer. Meteor. Soc.*, Vol. 85, pp 337-342.

[6]Hafner, T.,"Experimentelle Untersuchungen zum Druckwiderstand der Alpen" , Dissertation, Universität Karlsruhe, 1987.

[7]Hertzog, A., Boccara, G., Vincent, R. A., Vial F., Cocquerez, P., "Estimation of Gravity Wave momentum Flux and Phase Speed from Quasi-Lagrangian Stratospheric Balloon Flights.2: Results from the Vorcore Campaign in Antarctica", *J. Atmos. Sci.*, in press, 2008, see http://www.lmd.polytechnique.fr/VORCORE/biblio.htm

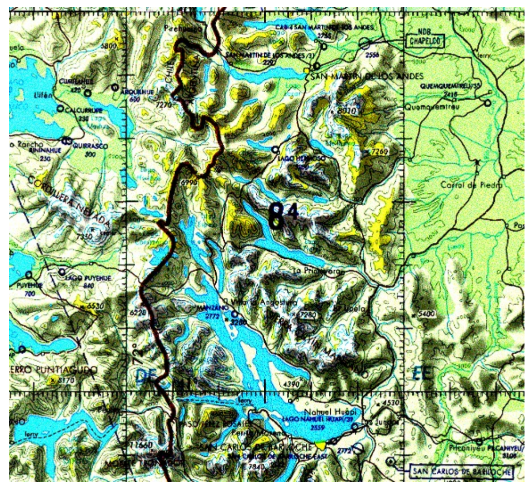

Figure 1 ONC-Map for an overview of the region between San Martin de los Andes and Bariloche.

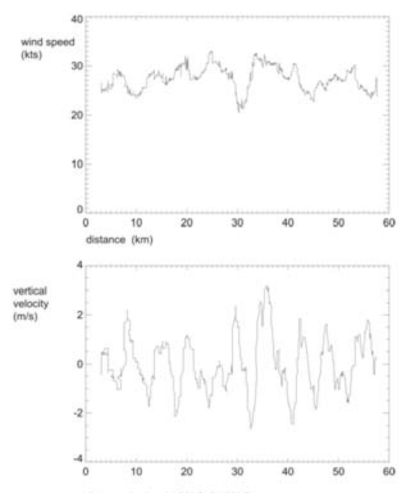

Figure 2 Flight 2 December 1999, Stemme S-10 (D-KMTE) San Martin de los Andes to Sierra de la Ventana, wind speed/distance, vertical velocity/distance. Note: the wind direction in Figures 2 to 5 is left to right with the mountains on the left.

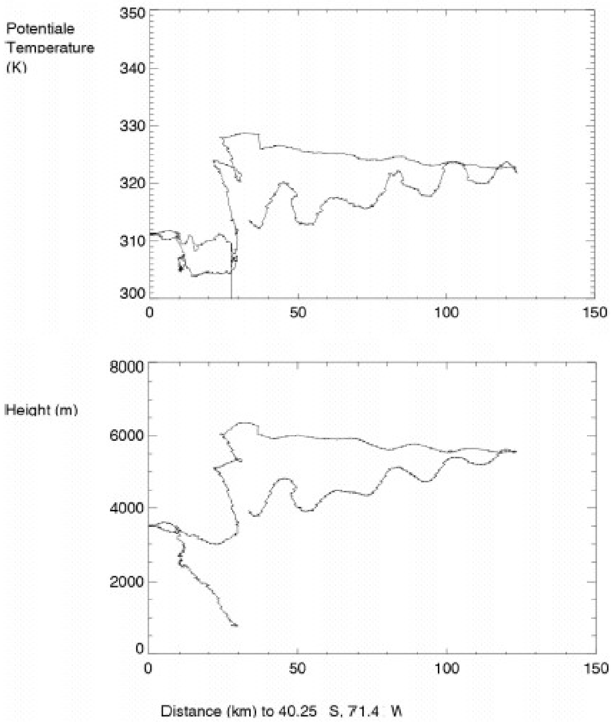

Figure 3 The height/distance and potential temperature/distance profile for the wave flight of December 3rd.

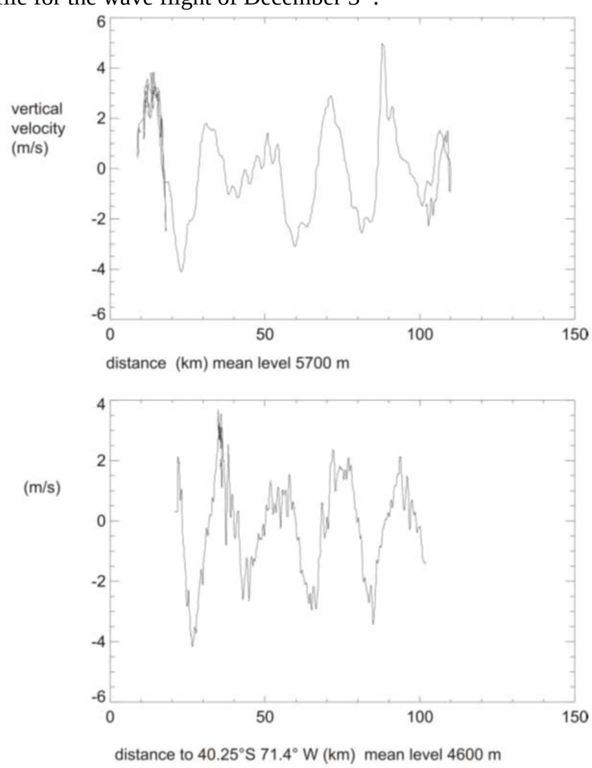

Figure 4 Flight 3 December 1999 Stemme S-10 (D-KMTE), San Martin de los Andes, lee wave Chapeico, vertical velocity (m/s), distance (km) at two different altitudes, crew: Lindemann/Olmann.

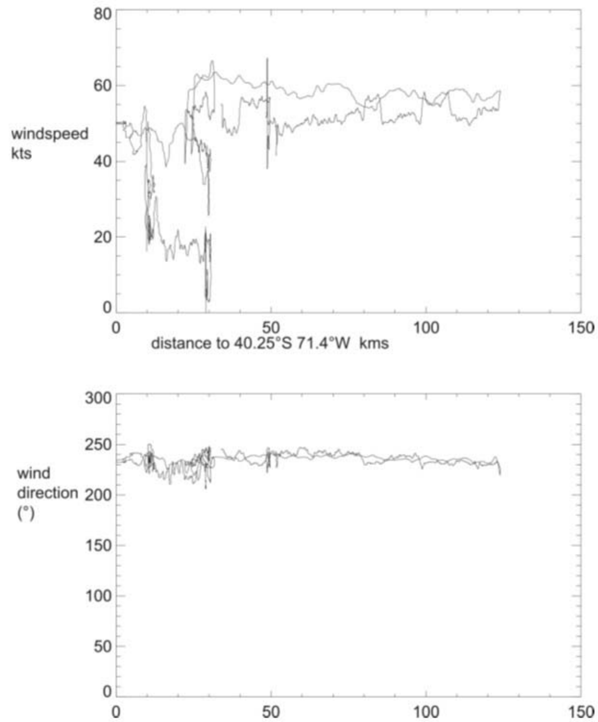

Figure 5 Flight 3 December 1999, wind speed/distance, flight from take off to end of file (wave Chapelco), mountain top 2400 m at km 14, 1200 m at km 26.

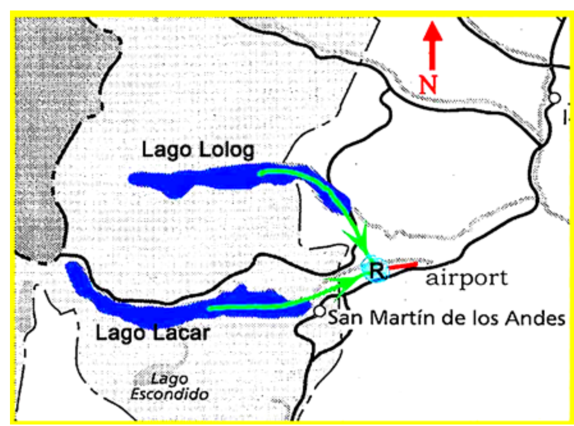

Figure 6 Channelled low level flow giving rise to a rotor like updraft at "R"