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ATMOSPHERIC CONDITIONS OF STRATOSPHERIC MOUNTAIN WAVES: SOARING THE PERLAN AIRCRAFT TO 30 km

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1. ABSTRACT

Mountain waves in the troposphere can and do become stratospheric mountain waves under certain meteorological conditions in locations around the world. Analysis shows that these waves will produce vertical wind speeds that will lift a specially designed sailplane potentially to an altitude of 30 km. The meteorological data analysis indicates that the best stratospheric mountain wave conditions required to get to an altitude of either 19 or 30 km in New Zealand are:

- strong low-level winds in a stable atmosphere (required for initial perturbation by mountains).
- a gradual wind increase with altitude to supply energy for wave amplification.
- a weak tropopause that allows for waves to traverse into the stratosphere.
- high-altitude winds (the polar vortex) in the stratosphere increasing velocity with altitude. The atmospheric conditions and their favored locations and seasons are discussed in this report.

2. INTRODUCTION

The first phase of a project for a sailplane to use stratospheric waves to reach an altitude of 30 km is currently underway. Stratospheric waves begin as mountain waves in the lower troposphere and propagate vertically under unique conditions. Sometimes, at favorable locations around the world, these waves propagate into the stratosphere, where they continue to propagate and amplify (increase vertical velocity) to altitudes higher than 30 km. The Perlan aircraft will be a highly specialized sailplane with a pressurized cockpit designed for very-high-altitude atmospheric research.

Currently, the Perlan aircraft is a conceptual design that has been modeled and investigated using a simulator. A primary project objective is to attain measurements that lead to better understanding of mountain waves and their effects on altering the stratospheric global circulation. Wind, temperature, and updraft measurements will characterize the wave development and propagation; therefore, the Perlan sailplane will be used as a measurement source augmented by temperature and speed sensors.

3. THE PERLAN PROJECT

The word “Perlan” is an Icelandic word meaning “pearl” and is the name given to this project, inspired by the mother-of-pearl or nacreous clouds occasionally seen at high altitudes and high latitudes. The mother-of-pearl or polar stratospheric clouds are usually visible when stratospheric mountain waves are present in the northern and southern hemispheres.

The Perlan project consists of two phases. Phase I will use a modified production Glaser-Dirks (Bruchsal, Germany) Flugzeugbau GmbH DG505M sailplane to reach an altitude of 19 km to demonstrate project feasibility. This phase will use pressure suits in an unpressurized cabin. Phase I will consist of flights over the southern Sierra Nevada mountain range during the winter and spring of 2002, followed by flights in New Zealand from June to August 2002. Phase I flight experience then will be factored into a high-altitude sailplane design, with unique aerodynamics and a pressurized cabin able to soar to an altitude of 30 km. Locations currently receiving consideration for phase II (30-km) flight activity include Sweden and New Zealand.

The current world altitude record for a sailplane is 14.942 km (49,007 ft) set by Bob Harris in 1986 near Mount Whitney in the Sierra Nevada mountain range of California. The previous record was set by Paul Bikle in 1961, also near Mt. Whitney, for an altitude of 14.106 km (46,267 ft). Before that, the record had been set by Larry Edgar in 1952, east of the Sierra, for an altitude of 13.492 km (44,255 ft). These records show that occasional conditions also exist at middle latitudes that allow a sailplane to climb through the tropopause into the lower stratosphere.

4. METEOROLOGICAL CONDITIONS

Mountain waves are the result of strong winds flowing over a mountain range in a stable atmosphere.[1] The stable nature of the atmosphere will generally restrict vertical motion of the atmosphere; however, the forcing caused by a mountain barrier has two effects. First, the barrier triggers oscillating wave motion in stable flow, similar to waves formed by water flowing over rocks

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in a fast running stream. Second, the forcing causes condensation within the lower moist layer of the atmosphere as air passes over the mountain barrier. The mountain wave presence is frequently revealed by distinctive lenticular clouds that form in the wave crest. These clouds form as a result of adiabatic cooling that cause atmospheric water vapor to condense as the air parcels are lifted. Note that sometimes the air mass might be too dry to form clouds in the presence of mountain waves.

For moderate mountain waves to form, several topographic and meteorological factors must be favorable:

- Low-level wind upstream of the mountain ridges should be at least 10 m/sec (20 kn).

- The wind direction is usually at right angles to the ridge (within 30°).

- Wind speeds should increase with height while wind directions remain fairly constant. If the wind speed increases too abruptly with altitude, the wave energy will tend to be focused or trapped within a low-altitude channel propagating downwind. If the wind speed decreases too abruptly with altitude over time, these downwind waves may either decay or at times become steeper, start to curl, and eventually break or collapse into turbulence.

- The size and shape of a ridge has little direct effect on the wavelength, but it does affect the amplitude. The mountain width—whether narrow or broad—will produce waves, provided the oscillation wavelength fits the mountain width. The resultant amplitude will usually depend on the mountain size, lee slope, and the degree of atmospheric stability.

- Wave propagation into and beyond the low stratosphere generally is favored by a weak or nearly undefined tropopause, minimal wind direction shift with altitude, and fairly consistent wind speed. Modestly increasing wind speeds with altitude permit the wave amplitude to grow without "breaking" or destabilizing as it propagates to higher altitudes and lower densities.

5. WHERE TO FLY

When in the stratosphere, the mountain waves propagate upward with increasing amplitude while generally maintaining a constant energy defined as air density times vertical wind–component squared (derived from the Eliasson-Palm theorem).[2] Figure 1 shows a depiction of the wave energy with altitude derived from balloon rise rate data on an excellent wave day. The rise rate oscillations observed are caused by the balloon laterally traversing with the wind into waves as the balloon rises. Figure 1 also shows the computed aircraft sink speed. The difference between the constant wave energy and the aircraft sink speed is the aircraft climb rate. On this particular day, the stratospheric mountain waves appeared to have enough energy to give a simulation of the Perlan sailplane adequate rate of climb to reach 30 km.

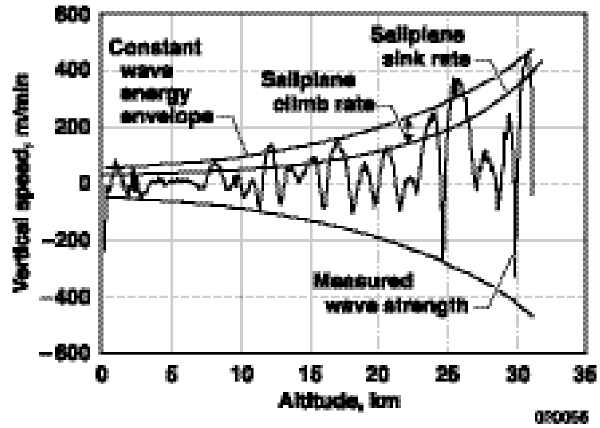

Figure 1. Vertical speed as a function of altitude over Lauder, New Zealand. Sailplane sink rates and corresponding estimated sailplane climb rates are plotted.

Figure 2 shows a balloon rise rate for an excellent wave event that occurred June 3, 1998. In contrast to an excellent wave day, figure 3 shows a balloon rise rate for a poor stratospheric wave event that occurred November 17, 1997. Figures 4 and 5 show north-south cross-sections of the tropospheric and stratospheric wind fields in the southern hemisphere along the 170-deg east longitude intersect during excellent and poor stratospheric wave events, respectively.

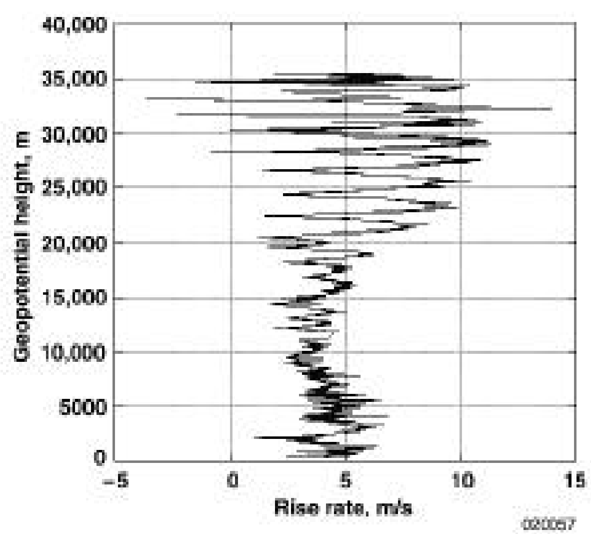

Figure 2. Rise rates as a function of altitude during an excellent wave event (2221 GMT June 3, 1998) at Lauder on the south island of New Zealand.

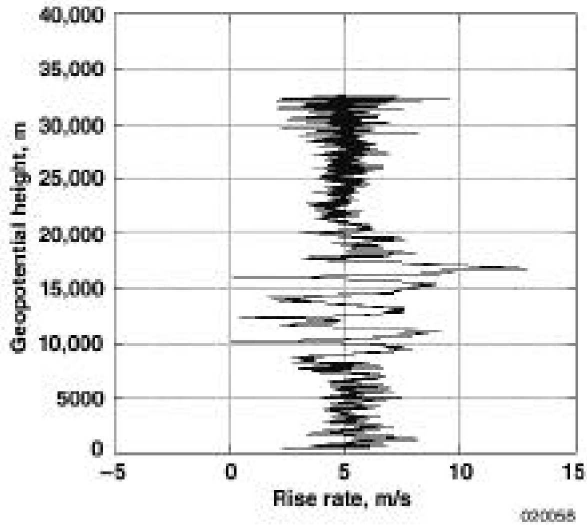

Figure 3. Rise rates as a function of altitude during a poor wave event (1957 GMT Nov. 17, 1997) at Lauder on the south island of New Zealand.

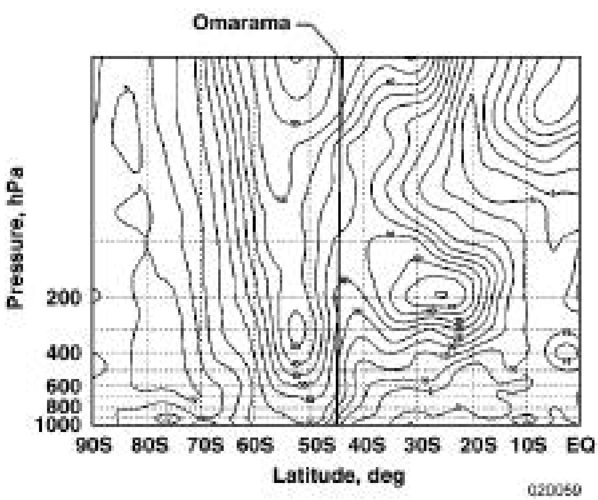

Figure 4. Cross section of winds as a function of pressure for June 4, 1998 (along 170° E longitude) from the equator to the south pole. This cross section represents a wind field for an excellent wave event. The latitude of the staging location in Omarama, New Zealand is labeled on this graph.

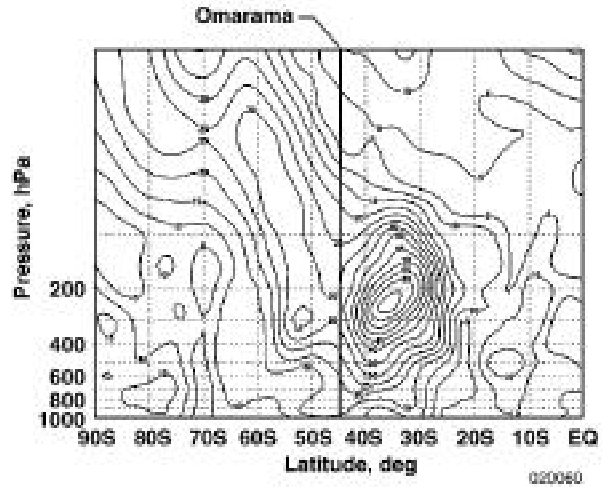

Figure 5. Cross section of winds as a function of pressure over the southern hemisphere (along 170° E longitude) from the equator to the south pole. This cross section represents a wind field for a poor wave event. The latitude of the staging location in Omarama, New Zealand is labeled on this graph.

Strong stratospheric mountain waves have been identified in the data from both northern Scandinavia and the south island of New Zealand.[3] The northern mountains of Sweden and the so-called "Southern Alps" of New Zealand easily perturb the low-level flow over the mountains, generating tropospheric waves. As these waves ascend through the tropopause, they interact with the high-level winds around the outer edge of the polar vortex, a dominant stratospheric feature that develops during the polar winters. The polar vortex develops and intensifies during the long, dark winter nights because of continuous radiative cooling of the atmosphere at these altitudes. As the polar vortex deepens, a strong pressure gradient develops near the day-night terminus (at approximately 60 deg latitude) in the stratosphere. The winds that develop form what is generally referred to as the polar night jet.

This polar night jet provides wind energy to the tropospheric waves that become stratospheric waves. Peak polar night jet winds reach a maximum near an altitude of 36 km (118,000 ft) at 80 m/sec (155 kn). The southern hemispheric polar night jet over New Zealand is more favorable for flight than the northern hemispheric polar night jet over Sweden, although it is located at lower latitudes (45° S as opposed to 68° north (N)). This favorability is largely because of the great size of the southern hemisphere polar vortex, which extends well into the low latitudes.

6. DATA

In support of phase I, a total of 149 soundings from two southern New Zealand sites were analyzed for wave criteria. The two New Zealand upper air balloon sites are Invercargill (46.4° S, 168.3° east (E)) which lies along the very southern coast of the south island and Lauder (45.0° S, 169.7° E), which lies inland and north of Invercargill is in the lee of the “Southern Alps.” As part of the World Meteorological Organization upper air network, Invercargill launches radiosonde balloons every 12 hr at 00 and 12 UTC. Lauder is not part of the World Meteorological Organization network and only releases balloons for special scientific research. The Perlan program has paid for balloon releases at Lauder during certain wave days. These 149 soundings were deemed “possible good wave days” by scientists at the National Institute of Water and Atmospheric Research in New Zealand. These soundings then were categorized as excellent, adequate, or minimal wave days, determined from the sailplane pilots experience.[5] These categories (table 1) were chosen on the basis of rise rates only. With increasing altitude, the density is reduced and true airspeed (climb, sink, and horizontal) is increased. Therefore, as sink speed increases, strong vertical wind is required to overcome the increased sink.

Table 1. Vertical speed requirements for sustained wave flight.

Altitude, km	Rise rates and description	
12	150 m/min	Excellent
	90 m/min	Minimal
19	210 m/min	Excellent
	120 m/min	Minimal
24	300 m/min	Excellent
	240 m/min	Adequate
	150 m/min	Minimal
30	425 m/min	Excellent
	365 m/min	Adequate
	300 m/min	Minimal

7. CHALLENGES

Although the goal of phase I is to reach an altitude of 19 km, much will be learned about how to get to an altitude of 30 km. One of the most significant feats will be getting the aircraft through the tropopause and into the stratosphere. As the Perlan sailplane reaches high altitudes, the Mach number will increase (0.07 at sea level, 0.33 at an altitude of 21 km, and 0.66 at an altitude of 30 km), and the Reynolds number will decrease based on the sailplane mean aerodynamic chord (1.46×10^6 at sea level, 4.41×10^5 at an altitude of 21 km and 2.07×10^5 at an altitude of 30 km). Soaring at high Mach numbers and low Reynolds numbers causes lift, drag, and control challenges with the aircraft. These challenges will need to be analyzed and solved before an altitude of 30 km can be obtained.

8. CONCLUDING REMARKS

Mountain waves in the troposphere can and do become stratospheric mountain waves under certain meteorological conditions in certain locations around the world. The limited data show that although not extremely numerous, waves do occur during the southern hemispheric winter that will permit an aircraft to reach 1an altitude of 19 km and possibly 30 km. Meteorological analyses performed have indicated that the best stratospheric mountain wave conditions required to get to an altitude of either 19 or 30 km in New Zealand are:

- strong low-level winds in a stable atmosphere for initial perturbation by mountains.
- a gradual wind increase with altitude to supply energy for wave amplification.
- a weak tropopause that allows for wave passage.
- high-altitude stratospheric winds (polar vortex) with increasing velocity with altitude.

9. REFERENCES

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