Title: Gravity wave over flat terrain.

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Abstract: Wave is everywhere throughout the atmosphere, whereever shear exists. Standing gravity wave is important because of its predictability and spectacular physics. Reports of widespread, workable lift over flat terrain, even with overcast conditions, has been reported. Satellite photos show that wave-cloud phenomena are common, though evanescent, involve geographically small areas, and often in weather traditionally not considered "soarable."

This paper reviews such wave conditions, and reports flight results. A flight program was devised, from which a single flight was feasible, though with interesting data that shows vertical movement to extend several hundred meters below cloudbase.

Keywords: gravity wave, flat terrain, undular bore, cloud streets, thermal wave

Introduction:

The research question concerns the conditions in which unusual soarable wave conditions may exist.

Atmospheric wave is everywhere; but not all wave is soarable. There is more wave that is generally realized, in conditions that seem poor for soaring, different from typical thermal soaring or mountain wave soaring.

Simplistically, the atmosphere is a stack of vast leaves of air moving across each other that differ in density (temperature, humidity), lapse rate, and/or velocity (speed or direction). These atmospheric leaves are relatively homogeneous; within them flow is generally laminar, and thus they have wide boundaries at which they interface.

Fluid flow is normally laminar unless disturbed. Soaring takes advantage of non-laminar flow. Consider water waves as analogous. A pond may be mirror smooth; then, a puff of breeze ripples the surface. The resulting wavelets have small breadth, short wavelength, and minimal height. They are not lined in rows. Consider flowing water: if it flows over a fixed irregularity, a standing wave is formed. Wave formed by wind moves with the flow.

Atmospheric wave is three-dimensional because vertical displacement.

Where there's difference across a boundary, and relative motion, there is undulant wave. When atmospheric moisture saturation permits condensation. linear cloud forms of several types may form.

There are several different forms of lined-up cloud.

- We are all familiar with thermal streets, in which clouds align with the wind in the boundary layer.
- Less well known is convective wave, in which lift aligns above cloudbase across the cloud face, as above a mountain or hill.
- Sometimes thermal streets interact with sheer above, creating a checkerboard appearance on satellite photos.
- Sometimes clouds are lined up in rows due to roll convection, in which the lift is not connected to a ground source and the sky may be completely overcast.

Not all atmospheric wave forms undulations or rolls. Some weather phenomena are analogous to water waves, in which energy is propagated across the air-water interface independent of any horizontal movement of the water. For example, frontal thunderstorm development occurs ahead of evolving storms, as unstable conditions propagate through the atmosphere, and dissipate behind, so that the "radar echo speed" of the storm exceeds the airmass speed in which the storm is embedded. Thus a squall line represents a wave phenomenon without having an undular appearance.

This research, is, however, focused on conditions that generate recognizable – and predictable – gravity wave where there are no orographic features to trigger or stabilize it. This may involve any of several types of atmostpheric periodicity:

·0 Stable: no wave; laminar flow, eddies damp out.

·1 Shear wave: periodicity due to difference of wind velocity (speed, direction) across a boundary (of density, humidity, temperature, velocity)

·2 Thermal wave (streeting). This is strongly affected by wind velocity and atmospheric instability.

·3 Convection wave involves periodicity enhanced by thermal penetration from lower layer to upper. This is strongly affected by instability of lower and stability of upper layer.

·4 Convective roll. This is less appreciated by most soaring pilots because it occurs in conditions that are less easily predicted, that are less comfortable for pilots (stronger surface winds in particular), and that may be difficult to reach without self-sustaining motors.

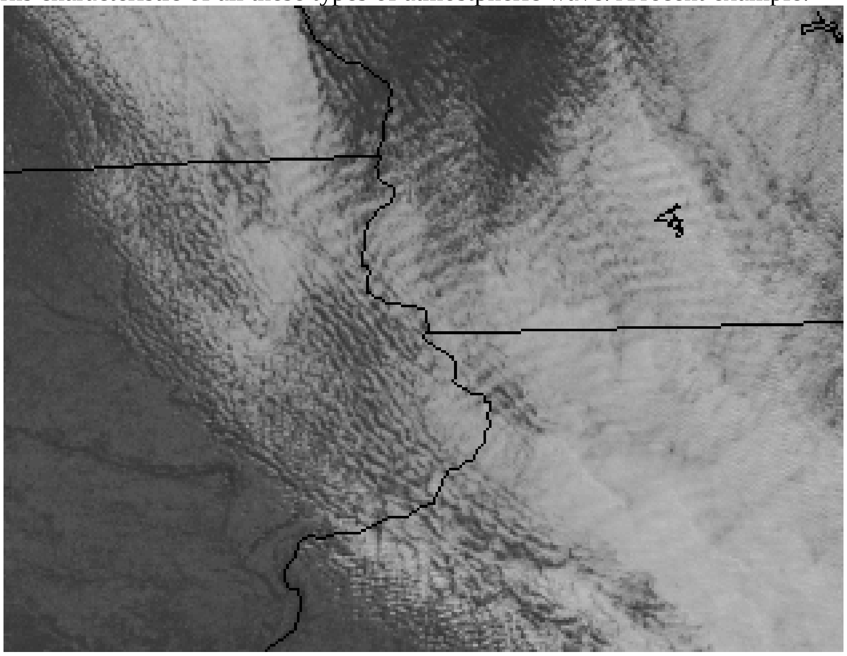
This is commonly seen on visible satellite photos in the overcast cloud disc behind cold fronts. The most famous convective roll is the Austrailian Morning Glory.

Convective roll development requires vertical windspeed shear with little direction change.

·5 Boundary wave is waviness at the interface between atmospheric layers with velocity shear across the boundary. Horizontal shear with little difference in wind speed appears to produce lovely thin wavy clouds. This phenomen is readily experienced in an airplane by flying just at the top of the haze layer. In this case, gentle pitch undulations of about .10-.30 Hz may persist for many kilometers.

Authors have speculated that roll convection must be triggered by some vertical displacement: I propose that boundary wave, for example at the top of the haze layer, or at the condensation level, is sufficient. Convective roll must be triggered differently from the mechanisms causing thermal wave (in which thermals condense and penetrate the sheared layer above) because its phenomology is completely different.

When satellite visible-light photos are studied, the cloud patterns near a low-pressure center often can be seen to contain, in different regions, patterns characteristic of all these types of atmostpheric wave. A recent example:



The broad cloud bands in this satellite photo ,19 November, 2016, 1300 UTC, the day following cold-front passage above southwestern Wisconsin, USA, are orthogonal to the gradient wind and represent convective roll. The narrower bands over eastern Iowa are thermal streets, aligned with the wind. 2-meter winds in this area were 15-25 kt with progressive speed shear to over 100 kt in the upper flight levels.

These conditions are typical after spring and fall cold-front passage over the flat terrain of the northern plains; one only needs to look at the southwest quadrant of low-pressure systems to find these patterns. Usability for soaring is mitigated by the strong winds involved and the difficulty predicting just where that quadrant will be located on any particular day.

Even if soaring pilots are not using these conditions, they are a source of annoying low-level turbulence to airline travellers.

In any case, the questions for the soaring pilot are whether this can be reached; whether it will endure long enough for flight; and whether the vertical velocities involved are enough to sustain flight. I propose that these conditions pertain more often than we expect, and that launching in windy overcast conditions and taking a high climb or tow, will sometimes turn out to be very interesting.

Thermal wave

Thermal activity creates vertical motion that in moderate wind velocities gathers thermals into rows-streeting, itself a complex wave phenomenon.

The base of cumulus clouds forms at the top of the haze layer. It was shown by Kuettner in 1957 and others, that the air lifted above cloudbase preserves the velocity (speed, direction) it had in the boundary layer.

If the wind above the boundary layer has a different speed, the cumulus presents a (malleable) boundary as a hill.

If the wind in the boundary layer creates streeting, rows of cumulus act as ridges.

If the wind above the boundary layer is approximately orthogonal to the wind below, this streeting will be augmented and thermal wave will be amplified. The challenge for soaring is that the required wind speeds are more than about 15 kt, a high-performance glider is preferred. Another challenge is that these conditions are rare.

If one studies post-frontal overcast, areas of wave are often seen. Sometimes there is no discontinuity; sometimes there are small clear breaks between long rolls. Typically, this is seen best far behind the cold front near the edge of the overdevelopment disc, where the roll clouds gradually fade, but presumably the rotor continues invisibly unless its mechanism requires the boost on the back side of the rotor that condensation would give.

If the wind above the boundary layer is approximately in line with the wind below, with a velocity difference that favors wave at the interface, streeting will be entrained by the wave and satellite photos may show a "checkerboard" cumulus array.

It is difficult to differentiate thermal wave from mountain lee wave when cumulus are being formed only a couple of hundred miles downwind from the range. In addition, lee wave would obviously augment thermal wave in ideal conditions.

A special situation that does not depend on actinic heating of the ground is the undular bore. This is a long, sausage-shaped, curved cloud that is most famous as the Australian Morning Glory.

This situation requires vertical velocity shear of about 2 kn per thousand feet or 3M/S per kilometer. Visible cloud also requires suitable dewpoint conditions so that the lifted air cools below its dewpoint in the upward-flowing part of the rotor.

Methology:

When waviness was observed in an overcase sky, and when work could be set aside, the airplane was launched: a Mooney 231 aircraft in which was mounted a GPS flight recorder. A stable climb was established at 2.5 M/S, 500 ft/min, into the gradient wind, to the base of the overcast. A 180-degree turn was then made, and the airplane flown near cloudbase that had an undulating appearance, then turned crosswind. The flight trace was downloaded to See-You flight analysis software and climb rates shown graphically.

Results:

On 13 March, 2016, wave conditions could be seen throughout the morning in the base of the overcast (Figure 1). Lift was encountered about 300 meters/1000 feet agl; and continued until near cloudbase at about 1500 meters/ 4800 feet agl – the depth of the roll convection was thus about 1200 meters/ 4000 feet, beginning just about at the usual altitude (Figure 2). During climb from ground to cloucbase, vertical air movement varied from -4 to +6 knots (Figure 3). During level flight near cloudbase, vertical velocities were similar: -2 to -3 kt to +2 to +4 kt. (Figure 4). The day's sounding showed both direction and windspeed shear (Figure 5). Research that includes cloud penetration has not yet been possible.

Conclusions:

Organized lift of usable strength was encountered from a conveniently low altitude above ground to (and surely into) cloud. This left extended across a wide local area, and the cloud base waviness persisted for several hours.

Additional flights that penetrate cloud and that explore the horizontal extent of this convective roll would be interesting. We already know from studying satellite photos that this lift is regional, and therefore will be more engrossing to pilots who want to extend their local and regional soaring-weather choices than to those wanting to set distance records by zipping back and forth over mountains. Still, oxygen masks or pressure suits won't be needed.

References:

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Bohme, T., Lane ,T. P., Hallc, W. D. and Haufa,T., 2007: Gravity waves above a convective boundary layer: A comparison between wind-profiler observations and numerical simulations. Q. J. R. Meteorol. Soc. 133: 1041–1055.

Figure 1: Cloud conditions

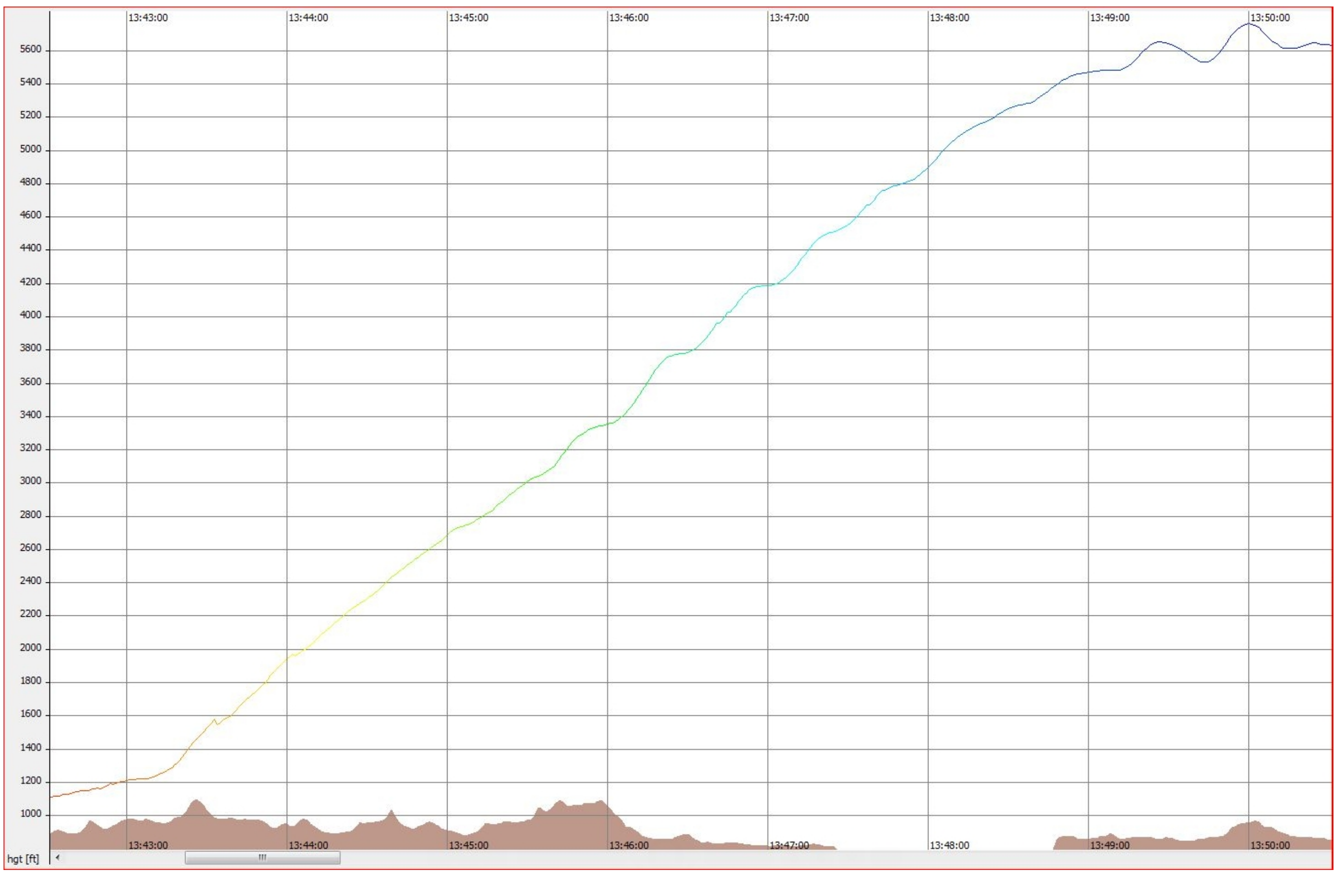

Figure 2: Climb cross-section: It can be seen that lift was encountered about 300 meters/1000 feet agl; and continues until near cloudbase at about 1500 meters/ 4800 feet agl – the depth of the roll convection was thus about 1200 meters/ 4000 feet, beginning just about at the usual altitude.

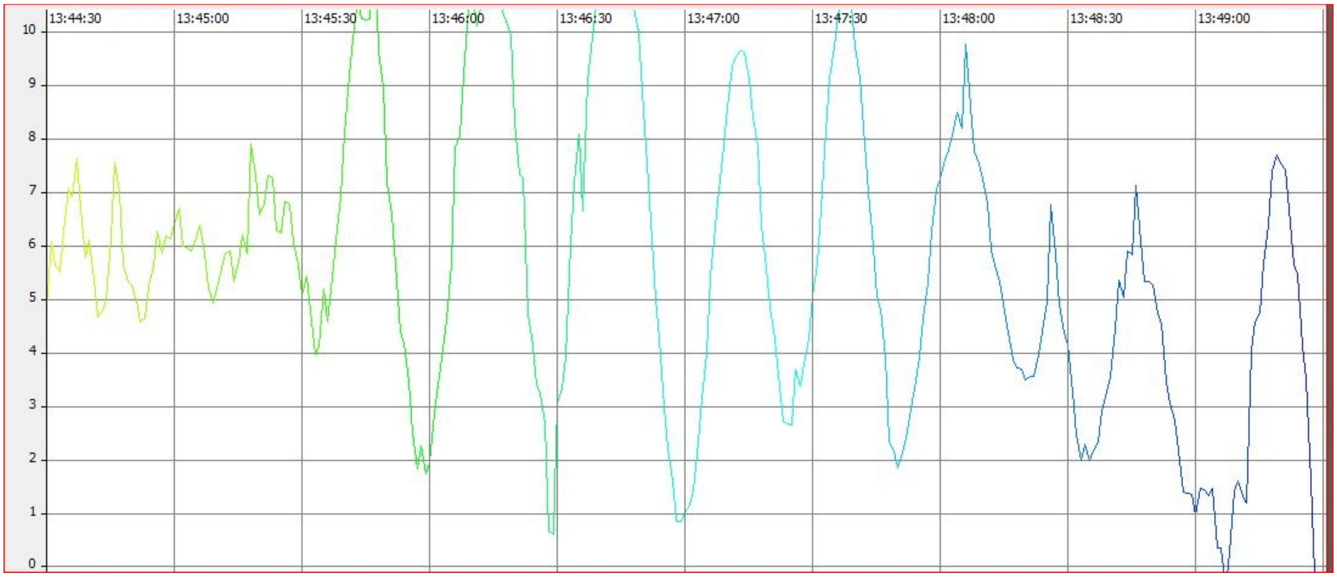

Figure 3: Strength of vertical movement during climb

The changes in vertical speed, in knots, are shown . The periodicity is short, about 30 seconds, related to the speed of the aircraft, about 100 knots. The aircraft's set climb rate of 500 ft/min (5 knots) means that the vertical air movement varied from -4 to +6 knots – very usable for soaring. (It was not possible to explore the lateral extent.)

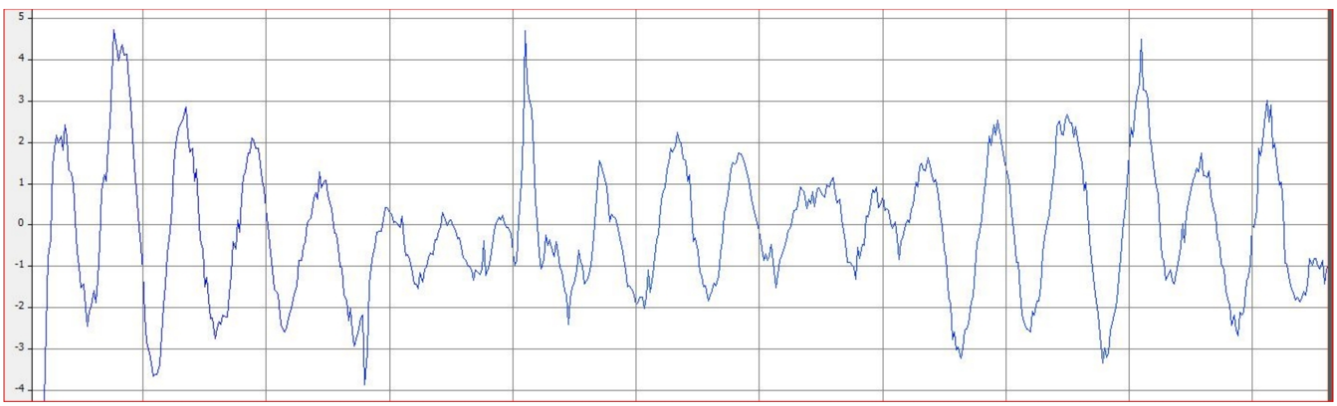

Figure 4: Strength of vertical movement during level flight near cloudbase

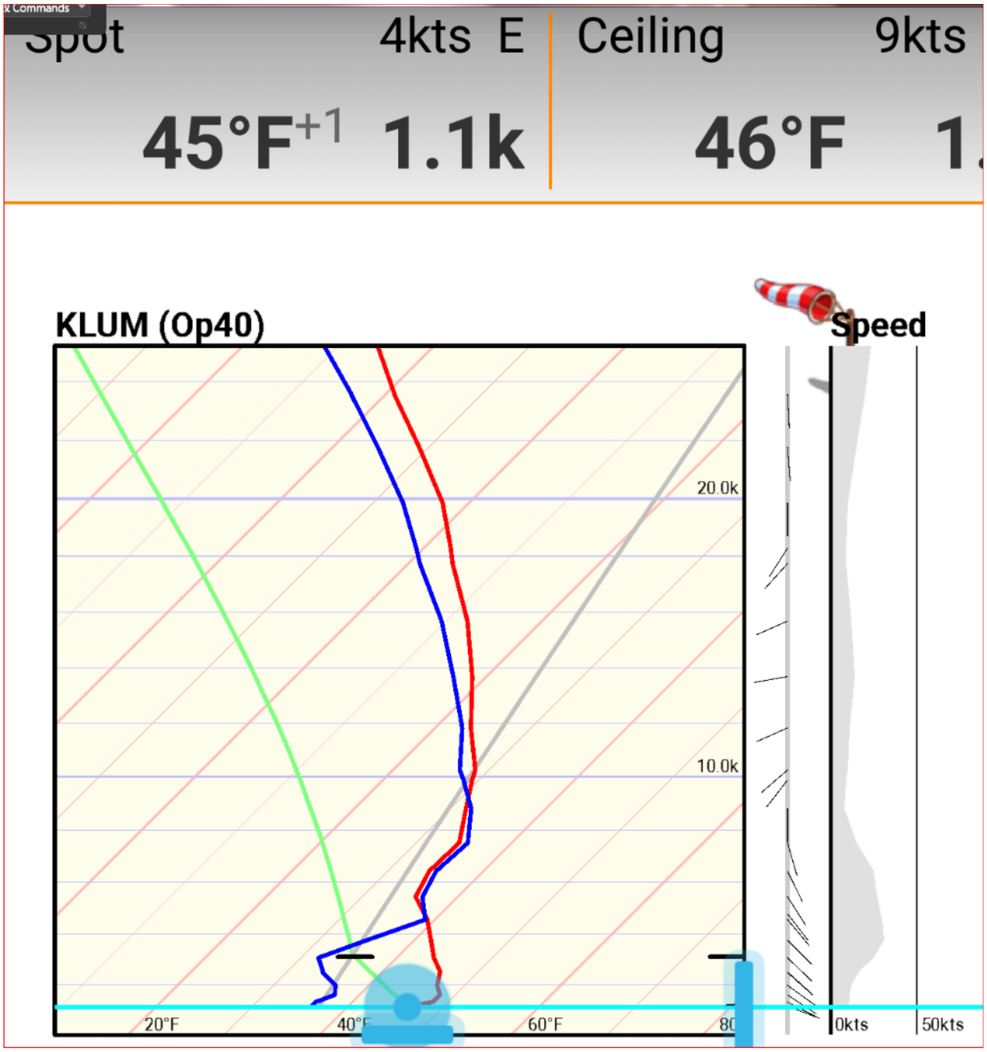

Figure 5: Forecast local sounding at 0900 hr, 13 March 2016