

Lee wave clouds

Abbreviations

DALR – Dry Adiabatic Lapse Rate, a straight line with a slope of -9.8 C per km of height
SALR - Saturated Adiabatic Lapse Rate, a curve with a slope that is always steeper than the DALR, and approaches it asymptotically at high altitudes as the air becomes very cold.
inversion
ELR – Environmental Lapse Rate, the variation of the temperature of the atmosphere with height.
LCL – Lifting Condensation Level, the level at which cloud forms when humid air is lifted
SA – Standard Atmosphere, a straight line with a lapse rate of -6.5 C per km from 0 to 11 km

Introduction

Wave clouds can be very deceptive and are often not what they appear to be. So, to overcome this problem, I have created some simple models that might help to explain them.

However, as previously quoted by Joerg: -“All models are wrong, but some are useful” George E.P. Box (1979),

The Standard Atmosphere (SA)

The most basic model of the atmosphere is the SA, which on a Stueve diagram is a straight line sloping at -6.5 C per km from 15 C at sea level up to the tropopause at 11 km, as in Fig.1. For the SA there is a level at which its ELR is tangential to an adjacent SALR curve. Below this level the SA is conditionally stable and acts as a convective layer. Above this convective layer the SA is absolutely stable. In winter the SA is displaced to the left and the convective layer becomes shallower. In summer it is displaced to the right and the convective layer becomes much deeper. Consequently, stable wave clouds can form at much lower levels in winter than in summer. In my model of three atmospheres with an ELR of -6.5 C per km, stable wave clouds can only form above the level at which the temperature is less than -10 C. In these models, their convection layer depths are 1,800 m in winter, 3,500 m in spring and autumn, and 5,000 m in summer, as in Fig. 1.

Atmospheric stability and humidity

For lee waves to occur the dynamic stability of the atmosphere, as determined by the Scorer parameter, needs to decrease upwards. This requirement is met by the presence of a stable layer, such an inversion or an isothermal layer, or by positive vertical wind shear. Directly above an inversion there is a highly convective layer, with a lapse rate that is much less than that of the SA ELR. These two layers look like an inverted nose superimposed upon the SA ELR.

Stable layers, such as inversions or isothermal layers, act as a lid on convection. As moist air is lighter than dry air it tends to rise until it reaches the base of a stable layer, and forms a spike in the humidity just below that layer, and this where wave clouds usually occur. If lee waves raise this humid air above its LCL, then cloud will form. Air condensing at the upwind edge of a wave cloud then flows along a streamline over its top before evaporating at its downwind edge. Consequently, wave clouds have a lens shaped cross-section, and are officially classified as alto-cumulus lenticularis. High level wave clouds are smooth with an elliptical outline, as well as having a lens shaped cross-section.

Lee waves tend to be aligned with linear topographical features, such as ridges or valleys, and consequently their associated clouds will take the form of longitudinal crosswind cloud bars parallel

to these features. These cloud bars form below an inversion, where the humidity tends to spike. lower level cloud bars usually have cumuliform tops, as in Photos 1 & 2, while higher level cloud bars may have smooth tops, as in Photo 3.

Immediately above an inversion there is a highly convective layer with a lapse rate close to that of the DALR. If condensation occurs in this layer, then convective clouds having the form of tiny castellanus or pseudo cumulo nimbus clouds can grow out of a wave cloud bar, as in Photos 4, 5 & 6. There may be several inversions, typically at low (cumulus), medium (alto-cumulus) and high (cirro-cumulus) levels.

Inversion penetration

The lifting of the atmosphere by waves affects the stability of the convection layer below an inversion. Dry air cools as it rises at the rate of 9.8 C per km (DALR). This alters the environmental lapse rate within the waves. If the air is cloudy then, as it rises, it cools at the SALR, which in the convection layer is less than the SA lapse rate of -6.5 C per km. If the wave amplitude increases with altitude below an inversion, then the ELR is further destabilised. This variation of wave amplitude, reduces the effectiveness of an inversion against cloud penetration, as shown in series of Figs. 2 to 7. Examples of cloud penetrating an inversion can be seen in Photos 7, 8 & 9.

Wave interference patterns

In complex topography, where the ridges and valleys responsible for the wave have different orientations, interference between wave fronts with differing angular orientations creates distinct patterns in wave cloud bars. When two ridges aligned at 45 degrees are equally effective in generating waves, this results in wave bars like sets of ladder rungs, with adjacent sets displaced by half a wavelength, as shown in Fig. 8. This effect can be seen in Photo 10 taken near Coburg..

When two ridges not equally effective, then the cloud bars have a meandering form, as in Fig. 9. If the cloud base is raised by a small amount, then the clouds become pillow shaped, as in Fig. 10, and in Photos 11 & 12. If the cloud base is raised sufficiently, as in Fig. 11, then only clouds with an elliptical outline will form. The meandering outlines show the original level of the airflow. Almost all smooth clouds with an elliptical outline are created by wave interference, and only occur at high altitudes where the atmosphere is completely stable.

When there are two equal ridges arranged at right angles, with the wind blowing over them at 45 degrees, then the waves create a pattern of square clouds like a chessboard, as in Fig. 12. If the cloud base is raised slightly, then the clouds remain square with rounded corners, as in Fig. 13, and in Photo 13. However, if the cloud base is much higher, then the clouds become circular, as in Fig. 14. Above these circles is a circular column, which is invisible when free of cloud. If the humidity is high enough, then cloud can form within these columns, as in Fig. 15. Depending upon whether the air of these columns is conditionally or absolutely stable, they will have either a cumuliform or a smooth surface. Photo 14 depicts a large column between two squarish clouds., as in Fig. 13.

Mounds and columns

Constructive wave interference can create local increases in the wave amplitude which are indicated by cloud mounds on the wave bars, as shown in Photo 15. A higher climb rate is likely to be found directly in front of their steeper front surfaces. Columns can join upper and lower wave clouds

together, as in photos 16, 17 & 18. If the cloud then dissipates from the bottom up, then there will be a shorter column hanging below the cloud above. These are wave clouds and the air passing through them rises and falls as it follows the streamlines of the wave. This is illustrated by the presence of divided columns, as in Photo 20.

Lee wave clouds in stratus layers

Lee waves create undulations in continuous cloud layers. If the vertical extent of the waves is less than the thickness of the layer, then they will only be visible from above. However, if their vertical extent exceeds the cloud depth, taking the layer below the LCL, then gaps will form in the wave troughs. These holes are liable to close unexpectedly if either the wave amplitude reduces or the humidity increases. When there is wave interference, the gaps have an elliptical shape, as in Fig.16.

If the top of a cloud layer is cooled by radiation upwards from its top, then negative convection can divide the cloud into cells, as shown in Photos 21 & 22. This effect is most likely to occur when lee waves form within a layer of strato-cumulus.

Wind shear

There are two types of wind shear. The variation with height of the wind velocity and its angular direction. Wind shear tends to occur at an inversion. The highest clouds normally take place when the vertical wind shear remains positive with little or no angular shear. An exception to this rule occurs when the angular shear increases the effectiveness of the topographical barrier as a wave generator.

Cloud walls and arches

If the air is sufficiently humid, then clouds can also form in the space between inversions. This region may be convective or stably stratified. A large patch of humid air passing through can then create a vertical cloud wall. If the air is only conditionally stable then the cloud will be cumuliform, but if it is absolutely stable, then the wall will be smooth like an iceberg.

An arch can form when negative vertical wind shear at the base of an inversion creates a rotor ahead of the wall. The top of the rotor draws cloud forwards along a curved arc to form an arch, as in Fig. 16 and in Photos 24 & 25.

Helmholtz instability clouds

Helmholtz waves result from instability due to wind shear. When the rising cooler air is moist, under the correct conditions, a characteristic cloud (also known as Fluctus), forms in the crest of each wave. These waves can break on top into cloud rolls. The axes of the cloud rolls are perpendicular to the wind shear. The wind shear is the result of stronger upper winds being separated from weaker lower winds by a stable layer in between, such as a temperature inversion. The clouds themselves typically occur at altitudes above 5,000 m. The wavelets in Photos 25 & 26 could be Helmholtz waves. Alternatively, they could be caused by inversion resonance.

Piles of plates

Piles of Plates occur when the humidity has a laminated structure, with adjacent layers alternating between high and low humidities. When the high humidity layers are raised to their LCLs, then elliptical or circular clouds can form at hot spots instead of columns. As these clouds are separated by the drier layers in between them, they look like a set of plates.

The humidity profile is affected by cumulus clouds upwind, which dissipate overnight into cloud shaped patches of moist air before reappearing downwind of mountains as wave clouds in the wave crests. The humid patches left by cumulus cloud streets upwind can be stretched by strong positive vertical wind shear into, almost horizontal, very thin laminations having alternate high and low humidities, as in Fig. 17, which is from “Clouds of the World” by Prof. R.S. Scorer.

Very large wave induced cumulus clouds can form along the range of mountains on the west coast of Scotland, which can be seen when flying high at Aboyne close to the east coast. When the cloud towers upwind of the central mountains decay away at the end of the day, the damp patches that are left behind are carried away by the wind. These patches are distorted by vertical shear into a set of almost horizontal layers having alternate high and low humidity, as in Fig. 17. The air between the clouds is stable, so that mixing ceases when the clouds evaporate and the laminations are preserved.

The Pile of Plates in Photo 26 originates from several large and very large cumulus cloud towers that formed the day before near the west coast of Scotland. The lenticular cloud above it suggest that this cloud is markedly elliptical. The various sizes of the plates are due to differences of humidity and possibly the diameters of the individual clouds forming the laminations. The uppermost plate has arched Foehn fingers, which suggests a rotor due to the wind speed decreasing at the inversion above it. The wind direction is indicated by these fingers, which are aligned with the airstream. The tiny spiky cumulus clouds beneath this Pile of Plates are very mysterious.

Witch's hats

The Witch's hats in Photo 28 have the shape of an inverted cone because their diameter becomes larger as the wave amplitude increases upwards below an inversion. The bulbous form is due to contiguous layers with variations of humidity. They are described in “Clouds of the World” as an unusual pile of plates, but as far as the air motion is concerned a fairly ordinary wave cloud.

Witches hats occur when the layers have varying humidity but are not separated by dryer layers. They have an inverted conical shape because their diameter becomes larger as the wave amplitude increases up to an inversion.