Kelvin Helmholtz Wave Cloud and Foehn Wall Cloud over the Front Range in a Stably Stratified Atmosphere

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Objective

The objective of the "Clouds First" assignment is to capture an image of a cloud phenomenon between the dates of August 22, 2016 and October 6, 2016. The image should embody the essence of the art of flow visualization by striking a balance between revealing the physics of the flow and achieving an aesthetically appealing picture.

Background

The following discussion provides some background of the relevant atmospheric physics present in this photograph.

Kelvin Helmholtz Instability

The Kelvin Helmholtz instability is a fluid instability that occurs in regions of high shear between two fluids with differing velocities and densities [1]. At a liquid-gas interface the difference in density is in the form of a jump discontinuity whereas in the atmospheric phenomena the instability forms in continuously stratified air i.e. continuous density variation. We will focus our attention on the phenomena as it occurs in continuously stratified air.

In a stably stratified atmosphere the density of a parcel of fluid that is perturbed upwards does not drop fast enough to match the density of the surrounding air and therefore experiences a restoring force due to buoyancy that tends to drive the parcel back down to the altitude where it started. Similarly an air parcel which is perturbed downwards feels an upward restoring force [2]. Thus the system tends to smooth out perturbations and maintain its present state unless some other source of energy is added to the system.

When a fluid of a certain velocity flows over a second fluid of a different velocity a shear layer occurs at the interface and viscosity produces a sheet of intense vorticity there. What happens next depends on the sensitivity of the system to small perturbations i.e. the stability. When the velocity gradient is small and the buoyancy driven restoring forces are relatively high a small amplitude perturbation introduced at the interface is damped out because the restoring force's tendency to restore stable stratification exceeds the tendency of the vorticity to amplify the perturbation. Alternatively, when the velocity gradient is high relative to the buoyancy restoring force a small perturbation at the interface grows. As the amplitude of the perturbation wave grows the fluid in the trough and crest finds itself surrounded by fluid from the other side of the interface which is moving at a different velocity. The difference in velocity of the two fluids at the same altitude causes the swirling motion and breaking wave appearance of the Kelvin Helmholtz instability [1].

Analysis of the stability of this flow type is possible with a few basic assumptions. First, the assumption is made that viscous effects are constrained to an infinitely thin sheet of fluid at the interface and that the fluid above and below the interface may be treated as inviscid and irrotational [3]. This allows the Navier Stokes equation (conservation of momentum) to be simplified to the Euler equation. It also allows the continuity equation to be satisfied implicitly by introducing the stream function. The Boussinesq approximation is invoked so that density is treated as a variable only in body force terms and as a constant elsewhere e.g. inertial terms. These assumptions can be used to derive the Taylor-Goldstein equation which serves as a governing equation for the behavior of parallel stratified flows [1]:

$$(U-c)\left(\frac{d^2}{dz^2}-k^2\right)\hat{\psi}-U_{,zz}\hat{\psi}+\frac{N^2}{U-c}\hat{\psi}=0$$

Where U is the velocity difference between the two fluid layers, c is a perturbation phase speed, ψ is the stream function, k is a perturbation wave number, and N is the Brunt–Väisälä frequency or the buoyancy frequency which serves as a measure of the degree of stratification in the atmosphere [2]. Complex analysis of the Taylor-Goldstein equation can be used to develop a stability criterion for this flow type [1].

We've seen that whether two fluids are susceptible to this shear instability depends on the magnitude of the velocity gradient between them and the buoyancy force. These two effects are related by the Richardson number:

$$Ri=\frac{N^2}{\left(\frac{dU}{dz}\right)^2}$$

When the Richardson number is high the buoyancy generated restoring force is high relative to the shear and perturbation growth is suppressed. Alternatively, when the Richardson number is low the fluid is susceptible to instability. It can be shown by considering gravitational potential energy and kinetic energy at the fluid interface that the parallel flowing fluids become susceptible to the Kelvin-Helmholtz instability when the Richardson number is less than ¼ [1].

Orthographic Lift: Wave Clouds and Foehn Wall Clouds

When moving air encounters a stationary solid body, like a mountain, it is forced up in elevation by the body. As it does so the air adiabatically cools due to expansion and the relative humidity rises. If there is sufficient water content in the air and the temperature drops enough the water vapor in the air can condense and form a cloud. Along the eastern slope of the Rocky Mountains the Chinook winds, which are a relatively warm moist westerly wind, condense into a cloud, known as a foehn wall, on the leeward (downwind) side of the mountains [4].

In a stable atmosphere the air which is forced up by the mountains descends afterwards as the system seeks to reestablish stable stratification. Buoyancy driven restoring forces carry the air back down to the appropriate altitude but the air will continue to descend past the stable point due its downward momentum. Now that the fluid is below its appropriate altitude an upward restoring force due to buoyancy develops. The fluid stops descending once all of the momentum is lost to buoyancy and is then driven back up towards its appropriate altitude. This process can repeat several times as the kinetic energy associated with the vertical momentum trades with the potential energy of gravity driven buoyancy [5]. Each time the air mass peaks in the cycle a new cloud can form downwind from the mountain if the conditions are right [4]. These clouds are known as wave clouds.

Method

Photo Settings

The photo was taken with a Canon 6D full frame camera and 24-70mm F2.8 lens. The camera was in aperture priority mode and the file was written to RAW format. A minimum sensitivity of 100 ISO was used because the scene was well lit and it was desirable to achieve a low noise image. Aperture was set to f/7.1 because that f-stop sits in the sharp range for the lens and provided enough depth of field for the scene. The shutter speed of 1/800 seconds was computed by the camera to achieve a balanced exposure and was sufficiently fast to allow the photo to be taken at that focal length without a tripod. Focus was set automatically by the camera on the plane of the Kelvin Helmholtz wave cloud. The lens was adjusted to a maximum zoom of 70mm to fill the frame with the Kelvin Helmholtz wave cloud. A summary of the photo settings with additional details can be found in table 1.

Focal Length	70mm
Shutter Speed	1/800s
Aperture	f/10
ISO	100
Autofocus	On
White balance	Auto
Gamut	sRGB
Format	RAW
Pixels WxH	4801x3429

Table 1: Photo settings

Location and time

The photo was taken on October 4th, 2016 at 8:42AM MT, 1 hour and 42 minutes after sunrise. The image was shot from Erie, Colorado, USA pointing 255° west. The range to the barn was roughly 135 meters and the distance to the edge of the Front Range was about 20 km. The camera was resting on a wooden fence post roughly 1.25 meters off the ground which was at an elevation of 1524m.

Post processing

The original image was shot in Canon RAW format. From the RAW file a 1/3 stop exposure bracketing was output into TIFF files. The bracketed files were loaded into Photomatrix Pro 5.1.1 and converted to a High Dynamic Range (HDR) image. The HDR method applied was a subtle and balanced approach that allowed details in the shadows and clouds to be pulled out without giving the image too surreal of an appearance. The HDR image was then edited in Photoshop Elements 5.0 to alter framing, color saturation on the land, lighting in the sky and to remove a few distracting elements, like a distant flock of birds, using the clone stamp tool. An unedited version of the original photo can be found in Appendix A for reference.

Composition

The framing and subsequent slight cropping of the image were done quite intentionally. Vertically the image has three distinct regions with 1/3rd of the frame filled by the land, 1/3rd filled by the foehn wall cloud and Kelvin Helmholtz wave cloud and 1/3rd filled by the sky above the wave cloud. The barn also sits 1/3rd of the frame right of the edge. These proportions give the image a pleasing "1/3rd rule" composition.

Results

In this image (Figure 1) the view is 255° W looking out at the edge of the Front Range north of Boulder, Colorado. Two-thirds the way up the frame a Kelvin Helmholtz instability is visible as a series of wave shapes in an elongated cloud. One-third of the way up the frame a foehn wall cloud is seen covering the mountain tops along the Front Range.

Figure 1: Kelvin Helmholtz instability and foehn wall cloud

Some insight into the atmospheric conditions on the day of the photo can be gleaned from the skew-T diagram generated from atmospheric sounding data taken at the closest weather station in Denver, Colorado (Figure 2). Interrogation of the dry adiabatic lapse rate curve and the CAPE (Convective Available Potential Energy) parameter, which was zero, reveal that the atmosphere was stably stratified at the time of this image. As previously discussed Kelvin Helmholtz instabilities are a feature of stably stratified atmospheres as are the wide flat clouds present in the image. Winds are seen to vary from the west to south west between 1500 and 7000 meters altitude and to increase in speed with altitude. The direction of the wind from west to east across the Front Range is consistent with the development of a foehn wall cloud and mountain wave clouds. The dew point curve reveals that the air at 5500-6500m had higher moisture content than the air above and below it. Typically this is where clouds would form. The skew-T diagram for Denver is slightly less relevant for the clouds observed in Figure 1 because they are a result of an interaction between the morning winds and the Front Range which is not captured in the data at the sounding station in Denver.

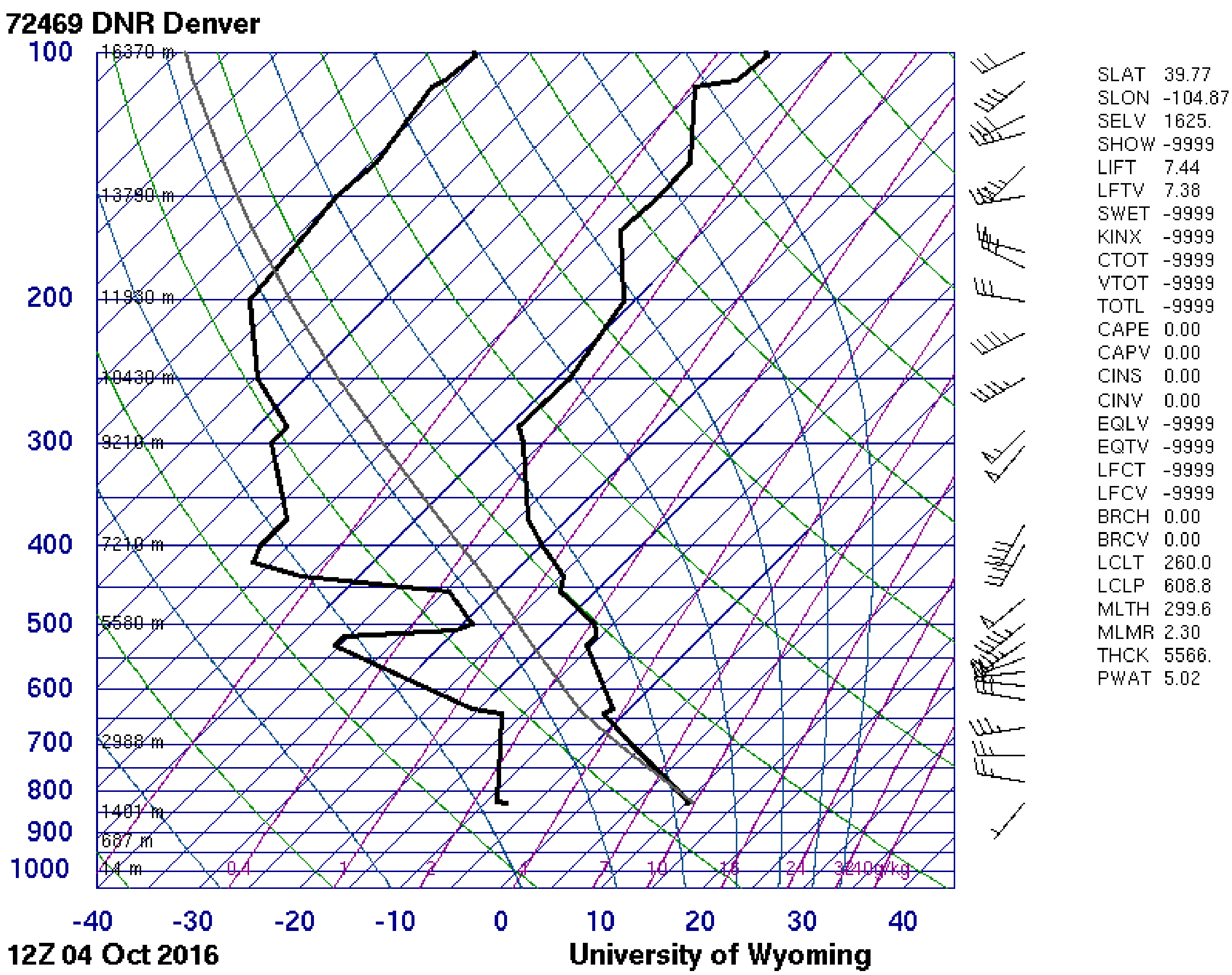

Figure 2: Skew-T diagram for Denver Colorado at 12:00 GMT [6]

Observations of clear Kelvin Helmholtz instabilities like the one seen in Figure 1 are relatively rare. These instabilities occur more frequently than visual survey would suggest but are not visible unless the conditions are right [3]. To be able to observe a Kelvin Helmholtz instability in the atmosphere a cloud must be present at the correct location and altitude to serve as a contrast for the fluid phenomenon. In this image the clouds which reveal the instability are most likely stratocumulus lenticularis based on their appearance, altitude and the atmospheric conditions [7]. In the image two rows of the lenticular clouds are present. These clouds are an example of wave clouds which have formed due to orthographic lift and subsequent oscillation of the altitude of the air after passing over the Front Range. The velocity shear needed to generate the Kelvin Helmholtz instability was probably also generated by the interaction of the prevailing winds with the topography in the region. The orientation of the Kelvin Helmholtz waves indicates that the winds were blowing south to north in the westerly facing image. If we attempt to apply the skew-T diagram to the location of this photo the moist conditions at ~6500m would be correct for cloud formation and the southerly winds at that altitude would be the correct direction to form the instability in the image. An altitude of 6500m above sea level would be roughly 3400m above ground level over the Front Range. This is slightly on the high side for a stratocumulus cloud [7].

Figure 3: Temporal development of the Kelvin-Helmholtz instability

The rollers of the Kelvin-Helmholtz instability in Figure 1 were relatively short lived, as is typical for this fluid phenomenon. The temporal progression of the flow field is shown in Figure 3. At 8:36AM the cloud which will serve as the contrast for the instability is just starting to form. By 8:41AM the rollers of the instability are fully developed (Figure 1 was taken at 8:42AM). Roughly 10 minutes after the instability became visible the mixing in the shear layer has mostly smeared out the roller flow pattern and the cloud returned to the flat shape typical of a stably stratified atmosphere.

The other cloud feature present in Figure 1 is the foehn wall cloud over the mountains in the Front Range roughly one third the way up the frame. The westerly wind direction creates the correct conditions for moist air flowing over the mountains to condense on their eastern downslope.

Conclusions

The weather on October 4th 2016 at 8:42AM in the Colorado Front Range created the necessary wind shear conditions in a stably stratified atmosphere to excite a Kelvin-Helmholtz instability. The presences of wave clouds produced by orthographic lift east of the Front Range made this interesting phenomenon visible for observation and photography, a relatively rare occurrence. The photographs documenting the 10 minutes during the development of the instability reveal the transient nature of this fascinating aspect of atmospheric fluid dynamics.

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Appendix A: Unedited image