Altocumulus Lenticularis over the Front Range in a Stably Stratified Atmosphere

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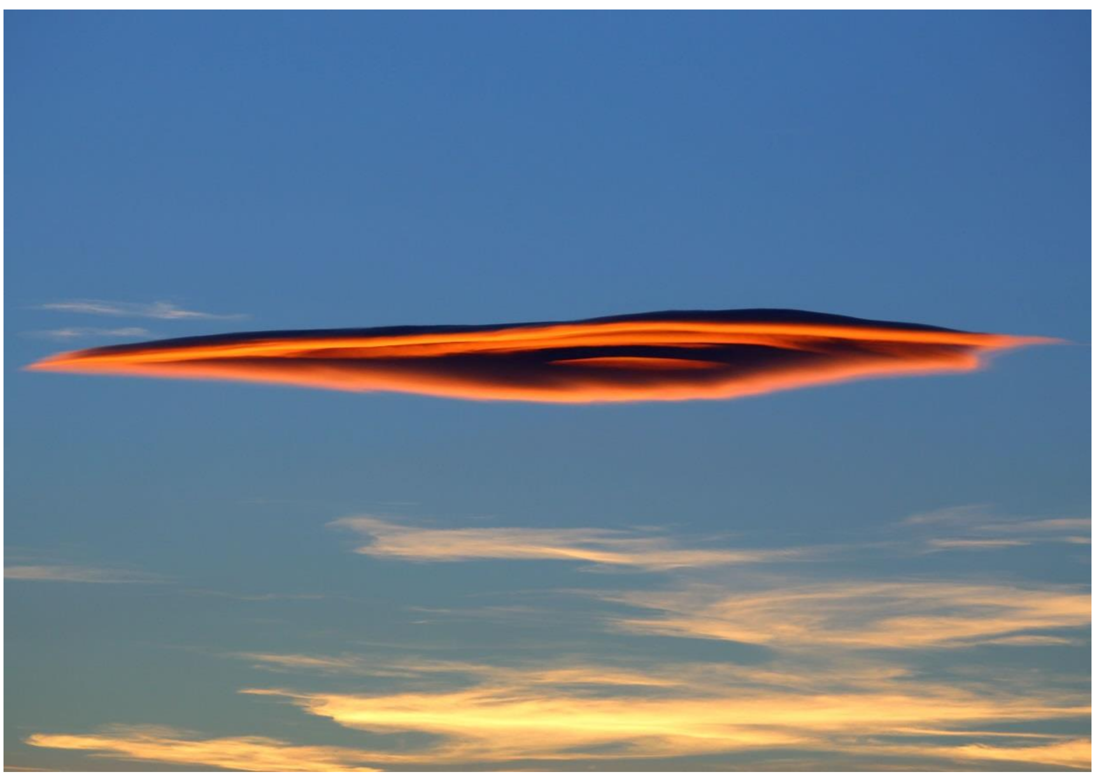

Objective

The objective of the “Clouds Second” assignment is to capture an image of a cloud phenomenon between the dates of October 7, 2016 and November 14, 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.

Orthographic Lift: Wave 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. The height at which the relative humidity reaches 100% is termed the lifted condensation level (LCL) and when air rises above the LCL the water vapor in the air will condense and form a cloud [1].

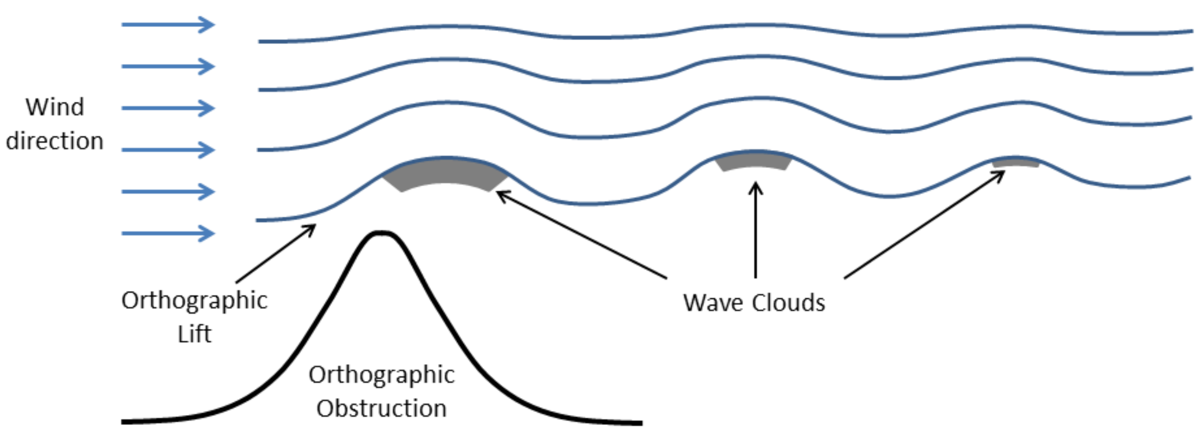

Figure 1: Orthographic lift and the formation of mountain wave clouds

In a stable atmosphere the air which is forced up by the mountain descends afterwards as the system seeks to reestablish stable stratification (Fig. 1). 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 vertical momentum is lost to buoyancy and is then driven back up towards its appropriate altitude. This process can repeat several times in a sinusoidal fashion as the kinetic energy associated with the vertical momentum trades with the potential energy of gravity driven buoyancy [2]. Each time the air mass peaks in the cycle a new cloud can form downwind from the mountain if the conditions are right [3]. These clouds are known as wave clouds.

Lenticular Clouds and Lenticular Stacks

Lenticular clouds derive their name from their lens shape [4]. As air flows over an orthographic structure like a mountain in a stably stratified atmosphere a cloud may form at the crest of the upward thrust of air (Fig. 1). The bottom of the cloud marks the LCL for that air below which the air has not risen far enough for water vapor to condense. This bottom boundary exists along air of roughly the same original elevation giving the underside of the cloud a flat concave shape consistent with the profile shape of the crest of the sinusoidal oscillation. Similarly, the top boundary of the cloud will have a flat convex shape above which the air has not passed through its LCL and therefore its water vapor has not condensed. As time evolves the lenticular cloud will remain fixed at the same point downwind of the orthographic obstruction but may be seen to evolve in place as the properties of the passing air vary e.g. distribution and amount of water vapor changes. Variations in the water vapor content or relative humidity of the air is responsible for another commonly observed feature of lenticular clouds. Along the lateral boundaries of lenticular clouds striations can often be seen which give the cloud the appearance of a stack of plates [5]. In extreme cases these striations can have such a large lateral extent as to separate the lenticular cloud into a series of floating disks. It has been shown that these lateral striations are due to differences in the relative humidity of the air at different elevations. Numerical simulations have shown that variations of as little as +/-0.25% in relative humidity can produce this effect [6].

Method

Photo Settings

The photo was taken with a Canon 6D full frame camera and 100-400mm F4.5-5.6 lens. The camera was in aperture priority mode and the file was written to RAW format. At the time of the image the sun had set behind the mountains to the west and therefore light levels were dropping. With a long lens there is a concern of camera shake compromising sharp focus in the image and so the ISO was pushed up to 640 and the optical image stabilization was turned on. To reduce camera shake the lens foot was set on top of a fence post. Aperture was set to f/6.3 which was closed enough to improve sharpness relative to shooting wide open but still open enough to allow a fast exposure time. Because the cloud was out at infinity the depth of field provided by an aperture of f/6.3 was more than sufficient to achieve an in focus image of the lenticular cloud and the higher clouds behind it. Shutter speed was computed in camera and the resulting value of 1/1600 seconds was sufficiently fast to get a sharp image with a 100-400mm zoom lens. Focus was set automatically by the camera on the plane of the lenticular cloud. The lens was adjusted to a moderate zoom of 235mm such that the lenticular cloud filled the frame. A summary of the photo settings with additional details can be found in table 1.

Focal Length	235mm
Shutter Speed	1/1600s
Aperture	f/6.3
ISO	640
Pixels WxH	5701x4000

Table 1: Photo settings

Location and time

The photo was taken on October 20th, 2016 at 6:18PM MT which was 5 minutes after sunset. The image was shot from Erie, Colorado, USA pointing 223° west. 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. The RAW file was first processed in Canon Digital Photo Professional software where the white balance was adjusted to drop the color temperature and recover shades of blue in the sky. The same software was then used to covert the RAW file to a TIF and output the image. The TIF file was then edited in Photoshop Elements 5.0. The image was rotated to align horizontal lines in the image with the bottom of the frame and the resulting image was cropped slightly to square up the rotated image. Finally the contrast was increased slightly. An unedited version of the original photo can be found in Appendix A for reference.

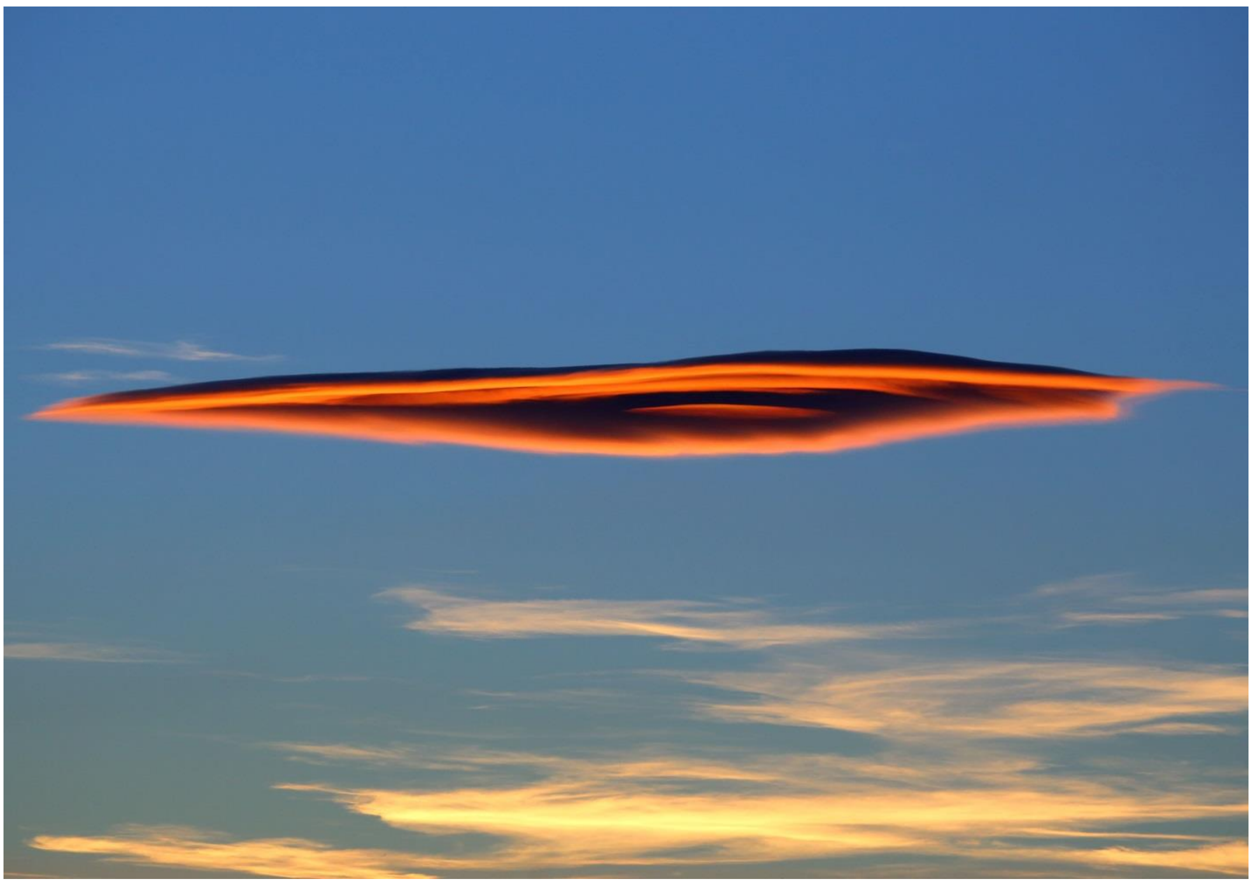

Figure 2: Altocumulus Lenticularis after sunset

Results

In this image (Fig. 2) the view is 223° W looking out at the edge of the Front Range north of Boulder, Colorado. The most prominent feature in the image is the bright orange lenticular cloud at the center of the photo. Reviewing the skew-T diagram (Fig. 3) from data taken at 6:00PM that evening from the Denver weather station provides insight into the atmospheric conditions. The CAPE (Convective Available Potential Energy) parameter has a value of 0.00 indicating that the atmosphere was stably stratified, which is a requirement for the formation of lenticular clouds. At higher elevations the wind was out of the West – North West which is consistent with this wave cloud forming on the easterly, leeward side of the Front Range. The air at lower elevations was relatively dry therefore this cloud probably formed between 5500 meters and 7500 meters where the relative humidity rises abruptly. With the terrain east of the Front Range sitting at roughly 1675 meters this places this moist stratum of air about 3825 to 5825 meters above the ground. Lenticular clouds at these heights above the ground are most likely altocumulus [4]. Therefore this variety of lenticular cloud is altocumulus lenticularis.

From this perspective the concave shape of the bottom boundary and convex shape of the upper boundary of the lenticular cloud are apparent. The lenticular cloud also has visible striations in the lateral boundary. One subtle striation is visible along the front lip at the center of the main cloud body and towards the right edge of the cloud. Underneath the main lenticular cloud a much smaller secondary lenticular cloud can be seen tucked up under the main cloud. These striations and voids are due to differences in the relative humidity of the air at different elevations. The smaller lenticular sits at the top of a stratum of air which has barely risen above its LCL and therefore is relatively small and thin.

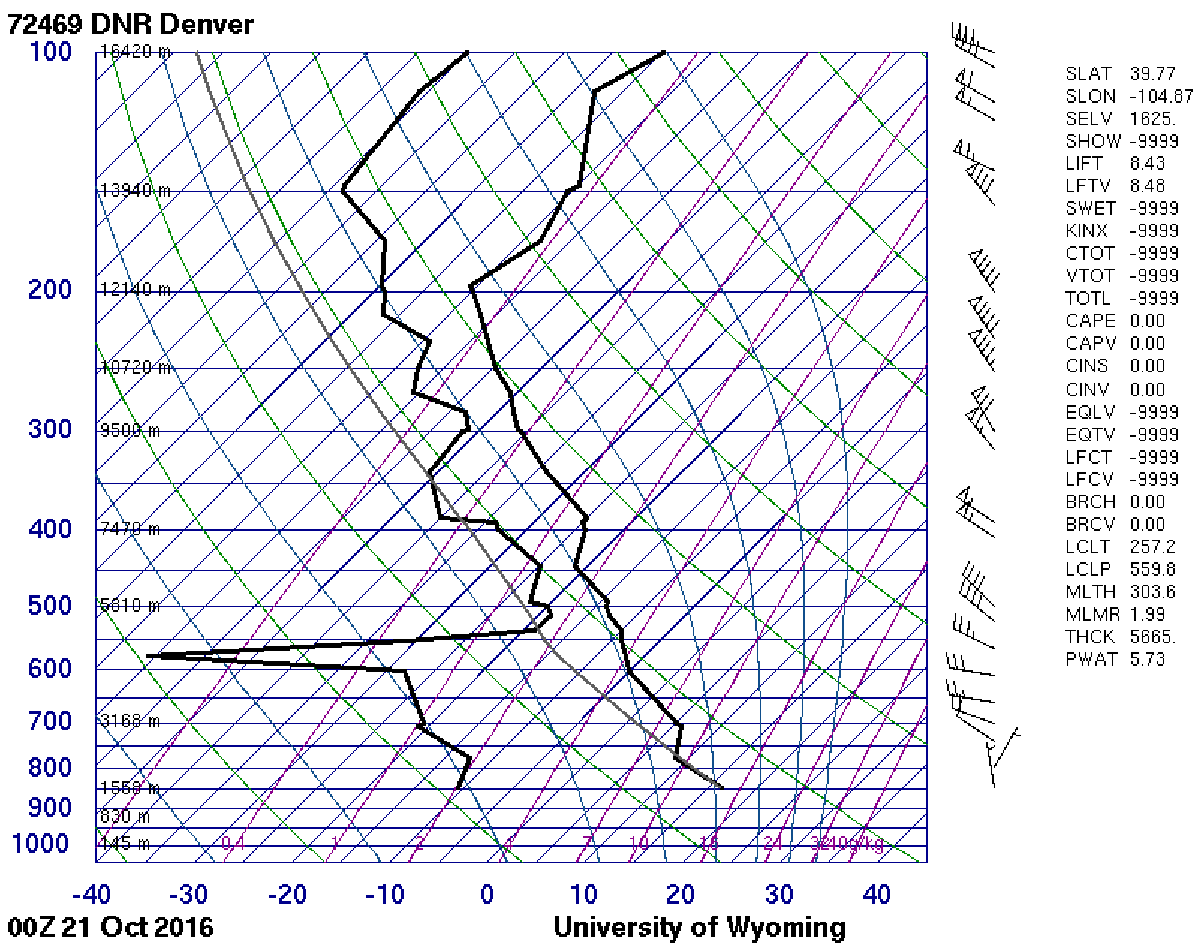

Figure 3: Skew-T diagram for Denver Colorado at 00:00 GMT Oct. 21, 2016 [7]

During the time which the cloud was observed it was seen to maintain its position relative to the ground but to vary in shape with time. The spatial extent of the cloud varied and the secondary lenticular was seen to disappear as conditions changed. As the sun continued to set the color of the cloud also progressed into more reddish tones. This progression can be seen in Figure 4 which was taken only 3 minutes later at 8:21PM MT.

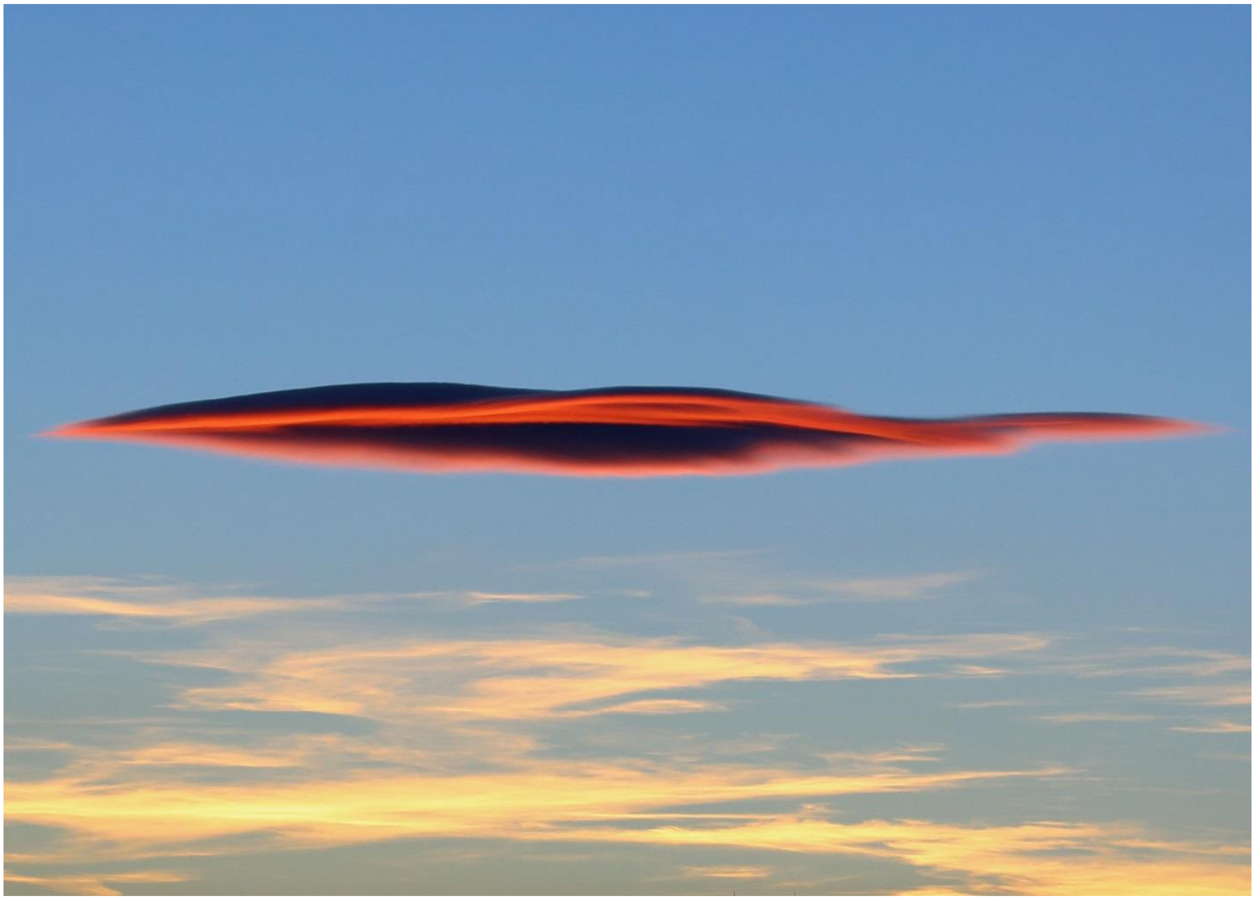

Figure 4: Altocumulus lenticularis 3 minutes after Figure 2

In the lower region of both images a different cloud formation is visible in the distance. The flat shape of these clouds and the most probable elevation range based on the skew-T diagram indicate these clouds are altostratus. The difference in color between the distant altostratus and the lenticular cloud is due to the angle at which the rays from the setting sun are hitting them. The lenticular cloud is more orange because the light hitting it has had to filter through more of the atmosphere than the light hitting the more yellow colored altostratus clouds. This most likely indicates that the lenticular cloud is lower in elevations than the altostratus clouds although the distance separating these two cloud formations may also contribute to the effect.

Conclusions

The stable atmosphere and westerly winds blowing past the Front Range on October 20, 2016 created the appropriate conditions for mountain wave clouds of the variety altocumulus lenticularis. The upper and lower boundaries of the lenticular cloud are consistent with the shape expected due to oscillations in the air mass due to orthographic lift. The lateral boundaries of the lenticular show striations of varying depths which are due to variations in the relatively humidity of the air at different elevations. In the lower portion of the image altostratus clouds are visible in the distance and the difference in color between these clouds and the lenticular cloud is due to relative heights of the two cloud formations. The lenticular cloud was observed over a period of time during which it was seen to maintain a constant position above the ground but to vary in shape and structure with subtle differences in the incoming air.

Acknowledgements

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Appendix A: Unedited image