MCEN 5151 – Flow Visualization Matt Phee

Clouds 2 Report

This is my image submission for the Clouds 1 assignment. For roughly a month, I have been actively seeking the types of conditions I believed would yield good cloud visualization. I sought to capture clouds at different times of day for lighting purposes, at different locations in the Front Range and continental divide areas, and at varying altitudes to view formations from different perspectives. The six images that comprise this collage capture the changes over time in an altocumulus lenticularis cloud over the flatirons of west Boulder.

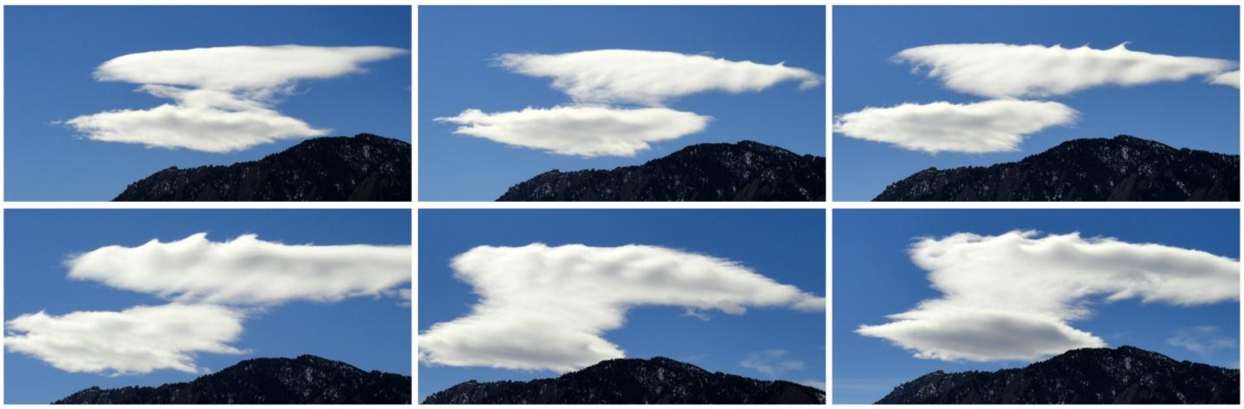

Figure 1: Clouds 2 image submission, Boulder, CO, 3/2/11, 1:06-1:13pm

This images were taken from the University of Colorado campus in Boulder, CO facing southwest over the flatirons. The camera was angled at roughly 30° from the flat horizon. The images were taken between 1:06 and 1:13 pm on March 2, 2011.

The cloud in these images is classified as altocumulus lenticularis and displays a clear Kelvin Helmholtz instability. Though it lacks the saucer shape characteristic typically displayed by clouds of the lenticularis species, all cumulus clouds formed by atmospheric interactions with mountains are classified under the lenticularis species. The complexities of the cloud prevent a clear observation of wind direction from the pictures alone. My observation was a moderate, Easterly wind, and Broomfield, CO weather data for 3/2/11 recalls a 5-10 mph wind to the Northeast [1]. The Skew-T data for Denver's 6:00 am sounding on this day suggests cloud base formation at an altitude of roughly 6000 m, the altitude at which the ambient atmospheric temperature approaches the dew point [2]. The Skew-T also shows the possibility of cloud formation higher at roughly 7800 m. My observations on 3/2/11 include a surprisingly diverse and chaotic array of cloud types and altitudes blanketing the sky. I do not believe the Skew-T plot's indication of only two possible cloud heights accurately represents the multitude of clouds I viewed. The altocumulus cloud imaged here, for example appeared to be much lower than 6000 m.

Cumulus clouds are formed by moist air uplifting in an unstable atmosphere. Parcel uplifting is governed by the relationship between the saturated adiabatic lapse rate γ_s and actual atmospheric lapse rate as in (1). T_p represents the parcel temperature and T_a is the temperature of the surrounding atmosphere [3].

$$\gamma_s = \frac{-dT_p}{dz} \qquad \gamma = \frac{-dT_a}{dx} \tag{1}$$

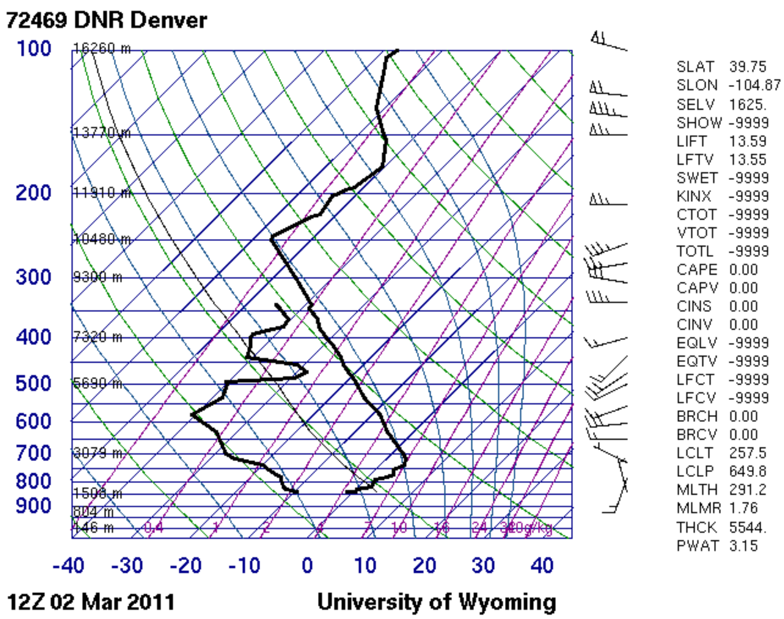

Figure 2: Atmospheric Skew-T plot, Denver, CO, 3/2/11, 6:00am [2]

Uplifting continues until rising parcels of saturated air are no longer warmer than the air surrounding them. This happens where $\gamma < \gamma_s$ and is called a stable atmosphere [4]. The Skew-T plot, shown in Figure 2, shows a temperature inversion between 1500 and 3000 m. The cloud appears to be trapped in a stable shear layer between opposing winds above and below. This suggests a relatively low cloud height of around 2000 m.

The primary focus of my collage is to demonstrate the subtle changes in the cloud's form due to surrounding wind and atmospheric conditions. The wave-like phenomenon that moves across the top of the cloud is called the Kelvin Helmholtz instability. Pijush Kundu defines the Kelvin Helmholtz instability as the "instability at the interface between two horizontal parallel streams of different velocities and densities, with the heavier fluid at the bottom" [5]. Further explanation reveals that the fluids need not have a finite boundary between them; rather the variation of velocity and density may be continuous over a finite region. The instability develops from the shear between fluid layers of different relative velocities. This may mean velocities in the same direction with different magnitudes or velocities in entirely opposite directions [5]. These scenarios are shown in Figures 3 and 4 respectively.

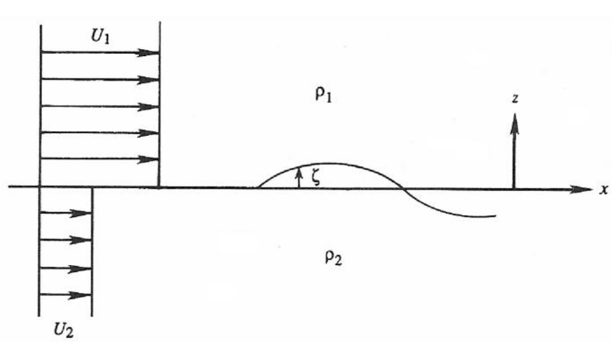

Figure 3: Discontinuous shear across a density interface where ρ_1 and ρ_2 are the fluid densities and U_1 and U_2 are their respective velocities

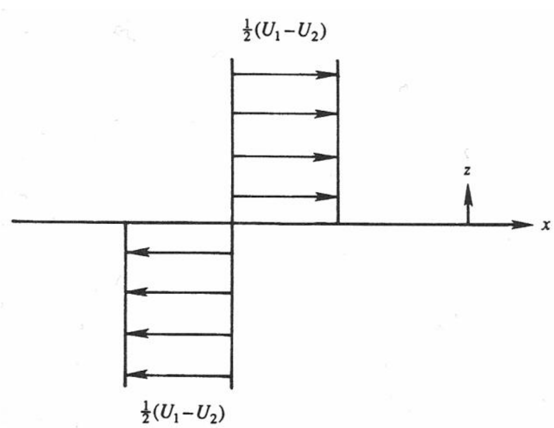

Figure 4: Background velocity field as seen by an observer with the average velocity $(U_1+U_2)/2$ of two layers

In either case, the shear results in the development of a vortex sheet as demonstrated below in Figure 5. The shapes of actual vortices depend on the relative densities of the fluids, which in the case of this simplification are the same. In the case of the pictured altocumulus cloud, the condensed vapor of the cloud is considerably denser than the air above it, leading to a less symmetrical shape. There does appear to be some interesting wind effects at work in the images. The instability waves formed with their crests to the right revealing the air above to be moving to the right. Despite the direction of crest growth, the group of wave crests are shifting together to the left which suggests the wind is actually flowing to the left. However, the body of the cloud appears to be surprisingly stationary with respect to the mountain. Furthermore, the final picture reveals a secondary Kelvin Helmholtz instability has formed in the opposite direction, indicating a different wind direction along the underside of the cloud.

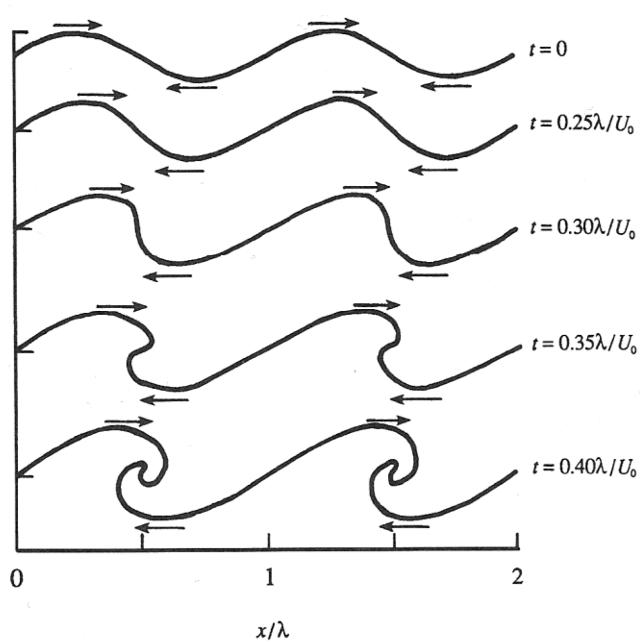

Figure 5: Nonlinear numerical calculation of the evolution of a vortex sheet that has been given a small sinusoidal displacement of wavelength λ

One more detail of note is the appearance of tendril-like formations on the leading and trailing edges of the cloud. There is a clear example of this on the right side of the cloud in the fifth image. This formation demonstrates how altocumulus lenticularis clouds can exhibit undulatus iterations that align themselves according to wind direction.

I chose to use basic color photography to capture this image. The way in which I approached the assignment was to have my camera on me at all times. I was determined to be prepared whenever a revealing or complex cloud formation presented itself. This approach mandated the use of a small, portable camera. My Sony Cyber-Shot DSC-H55 proved ideal in this capacity because of its relatively high picture quality and low physical profile. The image field of view was on the order of several thousand meters in width. The cloud was located approximately 3.5 km southwest of Boulder, and the Skew-T plot suggests a cloud altitude of roughly 6.0 km. Given Boulder's elevation of 1655 m, I estimate a distance between the camera and altocumulus cloud of 5.6 km. For these photos, the camera had a focal length of 18 mm, max aperture of 3.625, exposure time of 1/320 sec, f-stop of f/11, and sensitivity of ISO-80. The original digital images are TIFF files of 14.1 Megapixel (4320 x 3240 pixels) quality. To best demonstrate the changes in the cloud form, I resolved to compile six shots into a single collage. Using Adobe Photoshop Elements 8©, I cropped excess sky and foreground objects from the images and arranged them 3x2 into a new TIFF file with thin white borders between and around each image to visually distinguish it better from the rest. I also increased the contrast slightly in each image allowing the cloud to pop a bit more but not obscuring with the flow physics. The final collage image is quite large at 13222 x 4355 pixels and takes up 318 MB. A comparison of one of the original images and the final collage is displayed in Figure 6.

Figure 6: Before and after comparison of image post-processing

I am pleased with the outcome of this assignment. My final collage is both artistic and scientific in its presentation of altocumulus lenticularis subject to the Kelvin Helmholtz instability. I believe I accomplished my goal to take a photograph that clearly displays a scientifically defined and aesthetically pleasing cloud. I find it particularly exciting that I was able to observe such a distinct phenomenon in a short time period. I am still not entirely satisfied, and I wish the image contained a broader range of colors. As was my unsatisfied goal at the end of the first cloud assignment, I wish to capture cloud images that display the warmer colors that appear during sunrise and sunset. I was, however, able to satisfy my second goal from the first cloud assignment: I captured an orographic cloud formed by the mountains.

References

[1] Weather History for Broomfield, CO www.wunderground.com/history/airport/KBJC/2011/3/2/DailyHistory.html

[2] Skew-T plot. Denver sounding. Department of Atmospheric Sciences. http://weather.uwyo.edu/cgi-bin/sounding?region=naconf&TYPE=GIF%3ASKEWT&YEAR=2011&MONTH=03&FROM=0312&TO=0312&STNM=72469

[3] Cooper, C. David., and F. C. Alley. "The Effect of Lapse Rate on Vertical Stability." *Air Pollution Control: A Design Approach*. Long Grove, IL: Waveland, 2011. 624-26. Print.

[4] Cumulus. Glossary of Meteorology. American Meteorological Society. http://amsglossary.allenpress.com/glossary/search?id=cumulus1

[5] Kundu, Pijush K., Ira M. Cohen, P. S. Ayyaswamy, and Howard H. Hu. *Fluid Mechanics*. 4th ed. Amsterdam: Elsevier/Academic, 2008. Print.