Tracy Eliasson
Clouds 1 Final Report
10/27/2007
Flow Visualization

Figure 1

The image shown in Figure 1 was created for the “Clouds 1” assignment for the Flow Visualization course at the University of Colorado. The image shows a part of a cloud with undulations running throughout. Two types of clouds: altostratus undulatus and wave clouds are known to have this appearance. Altostratus undulatus are formed at the shear layer between 2 liquids by a phenomena called the Kelvin-Helmholtz instability. On days when altostratus undulatus form we expect to find a wind shear layer in the sounding data plot. These clouds typically have waves that run parallel, but sometimes, as was the case when this photograph was taken there are several undulatus in the sky with varying direction, often called biundulates[1]. Wave clouds are formed when a restoring force acts against momentum that is being transferred from the troposphere to the mesosphere. Gravity waves do not require wind shear; instead they happen as a result of liquids trying to come to equilibrium

[1] "Altostratus undulatus cloud." *Wikipedia, The Free Encyclopedia*. 14 Jun 2007, 14:12 UTC. Wikimedia Foundation, Inc. 11 Oct 2007 <http://en.wikipedia.org/w/index.php?title=Altostratus_undulatus_cloud&oldid=138132706>.

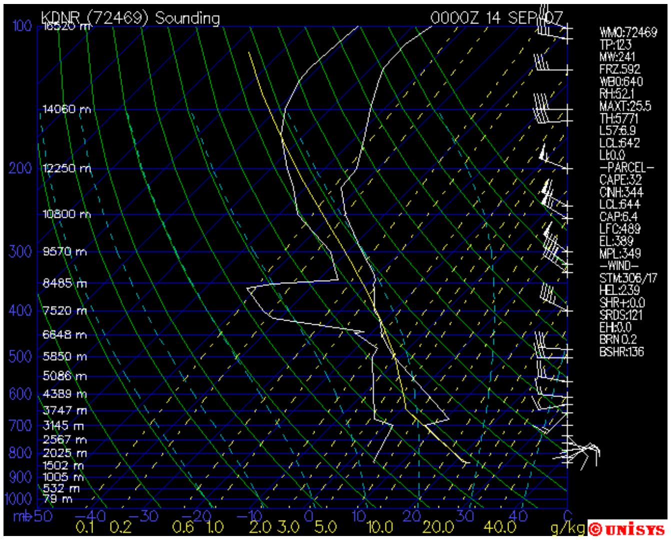

Figure 2a: Sounding Data
6:00 AM Weather Balloon

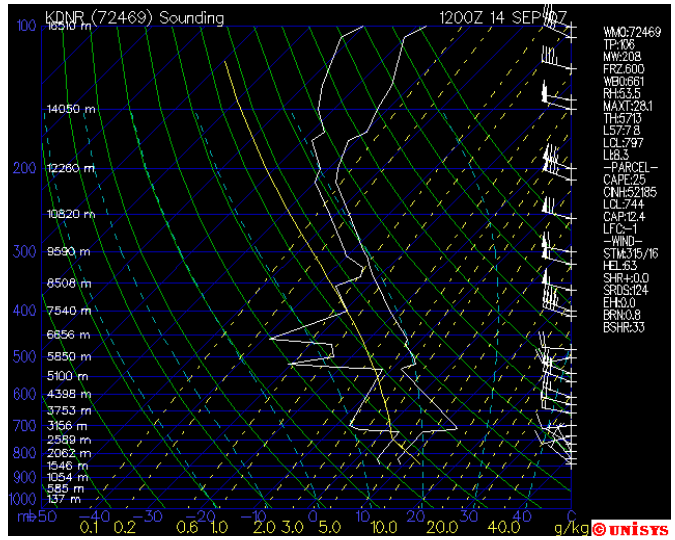

Figure 2b: Sounding Data
12:00 noon Balloon

after buoyant force has been applied[2]. Gravity waves typically do not cause multiple undulates clouds with waves in different directions. This fact leads the researcher to conclude that the cloud in Figure 1 is in fact an altostratus undulatus caused by the Kelvin Helmholtz instability. Discontinuities in the rolls can be seen within this image. This phenomenon is interesting because it is found in both nature and also in several technical applications.[3]

The photograph was taken on September 14, 2007 from the northwest corner of Arapahoe and Folsom in Boulder, Colorado. The camera was pointed in the southeast direction when the photograph was made. The time was approximately 7:50 am. Sounding data from the morning of September 14th is included as Figure 2a; sounding data from the afternoon of September 14th is included as Figure 2b. The cloud in the photograph is cirrocumulus undulatus. The elevation is approximately 9000 meters. According to the wind legend at the Unisys website[4] the wind speed at that elevation is approximately 48 knots, or 24.7 meters per second. It should be noted that a wind shear is needed to cause the Kelvin Helmholtz instability and no wind shear is present in the Skew T data, it is likely that the resolution of the Skew-T data (twice per day, location in Denver) was not adequate to capture the wind shear even that caused this. The Reynolds number is estimated to be 1.2E8, the calculation and assumptions are included as Appendix A. Another important dimensionless number, the Richardson

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[2] "Gravity wave." *Wikipedia, The Free Encyclopedia*. 16 Jul 2007, 04:13 UTC. Wikimedia Foundation, Inc. 11 Oct 2007 <http://en.wikipedia.org/w/index.php?title=Gravity_wave&oldid=144929684>.

[3] Browand, F.K., Troutt, T. R., "A note on spanwise structure in the two-dimensional mixing layer", *Journal of Fluid Mechanics*, **917**, 771, (1980).

[4] http://weather.unisys.com/upper_air/skew/details.html

Number, has also been calculated. The estimate for the Richardson number is 1.0, although uncertainty analysis puts it anywhere between .2 and 2.4. This number is a ratio of potential to kinetic energy[5]. The Richardson number helps to predict instability at the layer between two fluids, or at the boundary between to layers of the same fluid with differing velocities. A Richardson number of less than .25 indicates instability will be seen between the layers[6]. At the time that the photograph was made there were several large altostratus undulatus in the sky. There were also other clouds present including cumulus and cirrus fibratus. Presence of the fibratus, along with multiple undulatus with varied direction rollers, leads the researcher to believe that the waves are caused by the Kelvin Helmholtz instability. The clouds in the sky were changing rapidly so that the display of undulatus was completely over by 8:50 am. Figure 3 shows all three cloud types in relation to one another and also shows the varied directions of rollers within the sky. Figure 1 is a close up shot from the cirrus undulatus shown in Figure 3. Figure 4 shows a detailed view of the cirrus fibratus that is also shown in the lower right corner of Figure 3. All three photographs were captured from the same location and all 3 with the camera pointed in a southeast direction.

The flow visualization technique used for clouds in the sky is very similar to that of landscape photography. No special lighting or flashes were used. No special filters were employed. The most important thing to remember for photography of fluid physics in the sky is to always have your camera with you. This sky, like most, lasted only minutes.

The photograph was captured with a Nikon D80 camera. The lens is a 28–135 mm F/3.8-5.6.The focal length utilized was 135mm. The shutter speed was 1/400 sec with F/5.6. The ISO sensitivity setting was 400. The field of view in Figure 1 is 1000 m X 1000 m, related calculations are included as Appendix 3. The cloud was at an elevation of 9000 meters, therefore the distance from the camera to the object was 9000 meters. The original image was cropped to a 2592 x 2592 pixel square and the image levels were stretched with minimum setting 115 and maximum setting 208. No other image processing was performed.

The image reveals that fluid physics are demonstrated by clouds. It reveals that clouds can exhibit waves, just as water exhibits waves. Likewise waves in clouds can interfere with one another just as waves in water do. I like the level of detail available from the image. I also like that the image does not necessarily look like a cloud in the sky. The photograph is not just another landscape photograph. The texture and color are striking. Asked the subject matter a viewer is more likely to respond "fluid" or possibly even "liquid" before they respond

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[5] Wikipedia contributors. Richardson number. Wikipedia, The Free Encyclopedia. January 29, 2007, 02:39 UTC. Available at: http://en.wikipedia.org/w/index.php?title=Richardson_number&oldid=103990120. Accessed October 8, 2007.

[6] Wikipedia contributors. Kelvin–Helmholtz instability. Wikipedia, The Free Encyclopedia. September 13, 2007, 17:01 UTC. Available at: http://en.wikipedia.org/w/index.php?title=Kelvin%E2%80%93Helmholtz_instability&oldid=157646582. Accessed October 8, 2007.

“cloud”. The similarities between the waves in this cloud and the wind tunnel data from Broward are striking; unfortunately the confidence levels for the dimensionless numbers are not tight enough to conclude that the Richardson number predicts this flow. Further work could explore the estimates made for characteristic length and velocity in order decrease the uncertainty in the dimensionless numbers.


Figure 3: Cirrocumulus Undulatus, Cumulus, Cirrus Fibratus


Figure 4: Cirrus Fibratus

Appendix A: Reynolds Number Calculation

The Reynolds Number, Re, is a dimensionless number used to understand if a flow is in turbulent or laminar regime.

Re = v*L/ν where:

v = flow velocity
L = characteristic length of the flow
ν is the kinematic viscosity

Property	Estimate	Estimated Uncertainty (%)	Estimated Minimum	Estimated Maximum
Flow Velocity, v	24.7 m / sec	+/- 10%	22.2 m / sec	27.2 m / sec
Characteristic Length, L	60 m	+100% / - 75%	15 m	120 m
Kinematic Viscosity, ν	1.2 x 10^-5 m^2/sec [7]	+/- 10%	1.08 x 10^-5 m^2/sec	1.32 * 10^-5 m^2/sec
Reynolds Number, Re	1.24 x 10^8		2.5 x 10^7	3.0 * 10^8

The characteristic length L has been estimated by calculating the distance across the diagonal of the field of view (see Appendix 3) and dividing by the number of waves present.

[7] McDonald, A., Fox, R., *Introduction to Fluid Mechanics*, John Wiley & Sons, Inc, New York, (1992).

Appendix B: Richardson Number Calculation

The Richardson Numer, Ri, is a dimensionless number used to understand the Kelvin-Helmholtz instability, among other fluid flow phenomena.

Ri = gh / u^2 where:

g = acceleration due to gravity = 9.8 m / sec ^2
h = vertical length scale
u = representative speed

Property	Estimate	Estimated Uncertainty (%)	Estimated Minimum	Estimated Maximum
Flow Velocity, u	24.7 m / sec	+/- 10%	22.2 m / sec	27.2 m / sec
Characteristic Vertical Length, u	60 m	+100% / - 75%	15 m	120 m
Acceleration Due to Gravity	9.8 m / sec^2	0 %	9.8 m / sec^2	9.8 m/sec^2
Richardson Number	1.0		0.2	2.4

Appendix C: Field of View Calculations

The image was captured with a Nikon D80 digital camera. The sensor size on this camera is 23.6 mm by 15.8 mm. the lens focal length was 135 mm.

Field of View = FOV = (Distance to Object) * (Sensor Dimension) / (focal length)
FOV Height = 9000 m * 15.8 mm / 135 mm = 1053 m
FOV Width = 9000 m * 23.6 mm / 135 mm = 1575 m
Note that the final image was cropped to a square, utilizing the entire height available therefore the FOV of the final image is about 1000 m by 1000 m.