Towering Fair Weather Cumulus Clouds

JASON M. BOVE

Pennsylvania State University, University Park, Pennsylvania

(Manuscript received 20 April 2004, in final form 29 April 2004)

ABSTRACT

Photographs are presented that illustrate various swollen cumulus clouds found around the State College area on March 27th, 2004. As the clouds rolled by, the weather was partly sunny and there was no rain. The clouds have a cauliflower appearance and the well-defined flat bases represent lifting condensation levels (LCLs). Such clouds often arise on sunny days where heating occurs which allows an unstable temperature profile to arise in the boundary layer. Saturated air is also needed for the clouds to attain such vertical development. If the clouds continue to grow, they can eventually produce small showers as they can no longer support the water vapor. A chance of a shower is often imminent if the cloud bases turn a dark grayish color. The clouds taken on this day looked impressive, but other ingredients besides heating had to aid their formation.

1. Introduction

Fair weather cumulus clouds arise from instability (a lapse rate where temperature decreases with height) in the lower atmosphere. These clouds can grow taller and swell when there are steeper lapse rates allowing for more rising motion of air parcels. If they continue to develop, they can eventually form dark cloud bases and begin to produce small showers. The conditions needed for these clouds to form during the day will be examined. It will be shown what causes certain days to have little or none cumulus clouds while others have large distributions of taller, darker cumulus clouds. It will also be shown that the slope of the lapse rate is the cause of such clouds, and what other phenomena can cause the lapse rate to change.

2. Data

The source of the data are pictures taken by the author on sunny days in State College, Pennsylvania. These were taken with a Panasonic digital camera and 3x optical zoom. Pictures of several different clouds were taken at 2:00 pm EST (19Z). High cumulus clouds were captured with flat bases as well as cumulus clouds with a more traditional cauliflower appearance.

3. Observations

A cumulus cloud taken over a mountain on March 27th, 2004 in State College is shown in Fig. 1. A second cumulus cloud which is not over a mountain is shown in Fig. 2. These clouds exceed the vertical height of typical cumulus clouds. The clouds show evidence of more development as they display gray bases at the LCL.

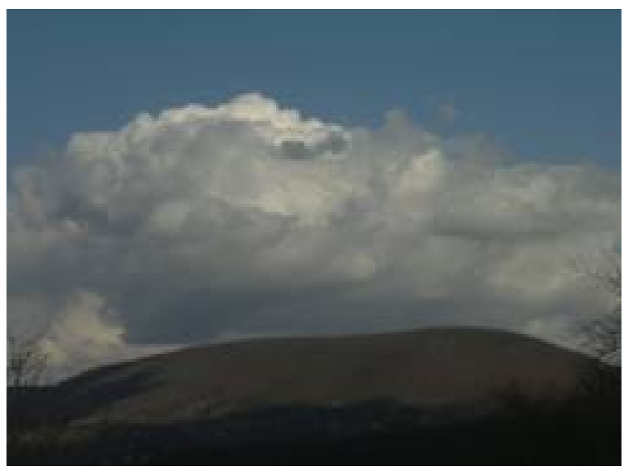

FIG. 1. Shown is a picture of a vertically built cumulus cloud over a mountain from March 27th, 2004. This was taken over State College.

Fair weather cumulus clouds taken in the early afternoon usually have not grown to this size. Usually, clouds of this magnitude require more diurnal heating to form. The sun heats the ground which in turn heats the boundary layer. Incoming shortwave radiation peaks in value

FIG. 2. Shown is a picture of a vertically built cumulus cloud from March 27th, 2004. This was taken over State College.

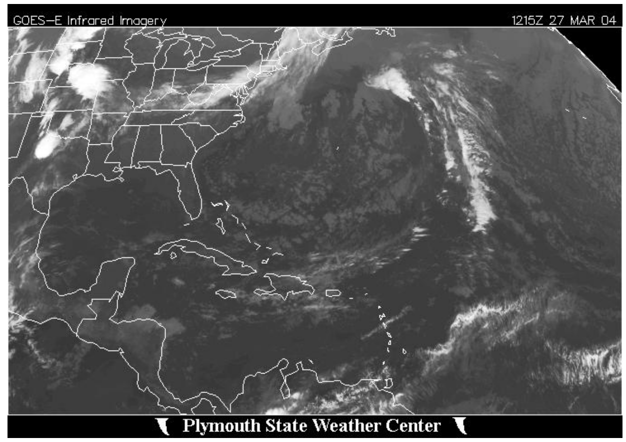

FIG. 3. Satellite image for State College at 1215Z.

FIG. 4. Satellite image for State College at 1915Z.

between the hours of ten and two pm EST. The ground absorbs this radiation and heats the boundary layer by emitting longwave radiation. These waves of radiation vary depending on the albedo of the surface. This is a timely process, and the daily high temperature usually does not occur until late afternoon because the ground is still emitting longwave radiation. The ground causes the air in the boundary layer to warm. The slope of the lapse rate becomes closer to dry adiabatic and the vertical temperature profile of the atmosphere near and above the boundary layer becomes steep. If there is cooler air aloft as the heating is occurring, rising motion of the air parcels begins to occur $(w > 0)$. This vertical motion is no where near the magnitude required to form thunderstorms, but it is enough to force parcels upward. As parcels move upward into cooler layers of the atmosphere, they lose their ability to hold water vapor and it condenses. The condensed water vapor is seen as cumulus clouds once the parcels reach their lifting condensation level. Daily heating was not enough to cause these clouds to form with such depth and so early in the day. When the cloud pictures were taken, the skies were sunny but it was not very warm. Also, observations indicate that the morning was cloudy with showers so heating from the sun was blocked. Something else had to cause the temperature contrast between the boundary layer and higher pressure levels of the atmosphere to increase. The heating of the day was not enough to allow the stronger rising motion to occur. Research was performed to determine if any other weather phenomena occurred which allowed the clouds to form. An infrared satellite image for 12Z on March 27th, 2004 is shown in Fig. 3, while Fig. 4 shows how it changed after 12 hours.

A cold front passed through the State College area and was causing precipitation in the middle and southern sections of Pennsylvania. Surface maps in Fig. 5 and Fig. 6 show the cold front passage. The frontal passage is further proven by the 850 mb temperature maps in Fig. 7 and Fig. 8 which show the wind shift that occurred before and after the cold front passed. At 00Z on March 27th, the 850 wind vectors were coming from the southwest. By 12Z, the winds in Pennsylvania began to shift from a southerly flow to a northerly flow. This was the time when the front was directly over the area and was about to pass through. The front passed through the area in the morning hours of March 27th at 12Z and the wind shift proves this.

A conclusion can be taken from this: cooler, denser air that the front brought was in place by the time the pictures of the clouds were taken. By 19Z on March 27th, 2004, the cold front had cleared the area. Drier air continued to filter in from the north. Further, the fact that the cold front was passing through the area in the morning indicates that clouds associated with it were around until mid-morning. This blocked possible heating from the sun in the morning hours so that it did not really start heating the ground until around 10 am EST (15Z). Radia-

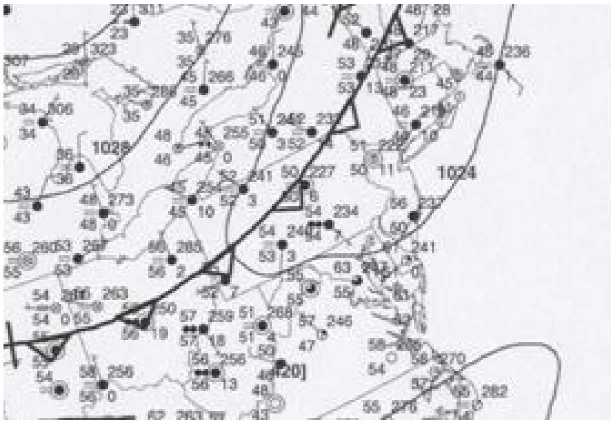

FIG. 5. Surface map for 1200Z for Pennsylvania on March 27th, 2004.

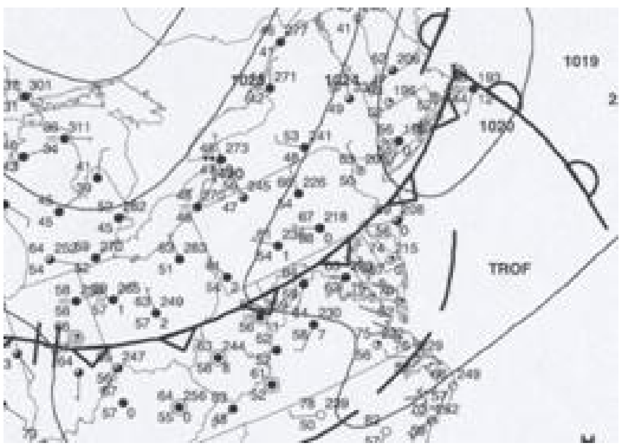

FIG. 6. Surface map for 1800Z for Pennsylvania on March 27th, 2004.

tion from the sun had only been incident upon the ground for about four hours. The frontal slope can be calculated by:

$$\frac{dZ}{dY} = \left(\frac{f\bar{T}}{g}\right)\frac{U_{gw} - U_{gc}}{T_w - T_c} \tag{1}$$

where f is the Coriolis parameter, $\bar{T}$ is the mean temperature across the front, and g is gravity. U_{gw} and U_{gc} are the geostrophic wind components parallel to the front on the warm and cold sides. T_w and T_c are the temperatures in Kelvin on the warm and cold sides. This equation reveals that the cold front's slope was only about $\frac{1}{384}$. This implies that cooler, denser air was still entering the higher pressure levels of the atmosphere later in the day. The front was weak and did not cause a real surface temperature change. On this day, the high temperature was the same (70°C) as the day before. A small frontal slope caused the cooler, drier air to invade the surface first. This pushes the warm air at the surface upward and forces it to condense and form the visible clouds. However, radia-

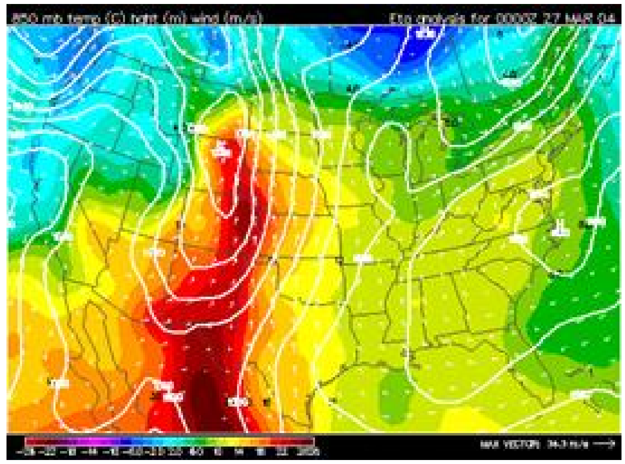

FIG. 7. Temperature and height variations for the U.S. at 850 mb for March 27th, 2004 (0000Z).

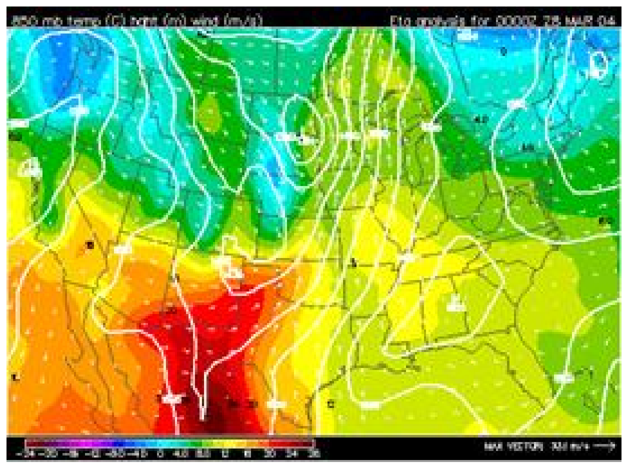

FIG. 8. Temperature and height variations for the U.S. at 850 mb for March 28th, 2004 (0000Z).

tion from the sun was heating the ground at the same time as the frontal passage. The grounds longwave radiation caused heating of the so called cooler air immediately so that no real temperature change could be felt. Thus the cold front brought slightly cooler air to the upper layers of the atmosphere while the sun warmed the colder air at the boundary layer. This small contrast brought the cloud development so early in the day. The change in the winds from the front also allowed some good orographic lifting to occur. The northerly winds caused by the front were directed into some of the mountains located eastward. In particular, the picture in Fig. 1 is a cloud taken over Nittany Mountain. The topography of Pennsylvania map shown in Fig. **??** shows that higher elevations are located to the north of State College. This cloud has a much more enhanced vertical build as the northerly winds were forcing the parcels upward. The vertical velocity, w, can

FIG. 9. Topography of Pennsylvania. The location of State College is indicated.

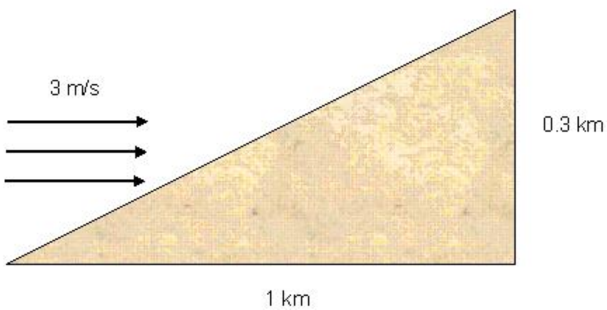

FIG. 10. Schematic of how Nittany Mountain effects the direction of the wind.

then be calculated to see how fast and how long it takes a parcel to reach the mountain peak based on the mountain alone. The height of Niittany Mountain is about 0.3 km and the horizontal distance to the peak is 1 km. The structure of the mountain is shown in Fig. **??**. The following equation can be used to calculate how the mountain causes parcels to rise,

$$T_s = \left(\frac{w}{U}\right) \tag{2}$$

where T_s is the slope of the terrain, w is the vertical velocity in z coordinates, and U is the mean wind colliding with the mountain. Using a slope of $\frac{3}{10}$ and a mean wind of 3 m/s, a value of 0.9 m/s (3.24 km/hour) is obtained for the vertical velocity based on lifting from the mountain. Knowing the height of the mountain, the time it takes for a parcel to reach the top of the mountain from the mountain slope is 6.11 minutes. This is a rough idealistic estimation of the vertical velocity and does not take into account some assumptions. First, the mountain is not a perfect triangle as the terrain is bumpy and curved. Secondly, the wind speed did not remain constant at 3 m/s the entire time. This is an average of the general wind speed in the hours before the clouds formed. The cloud in Fig. 1 is rising over a mountain and has such depth from both the vertical temperature contrast and the oragraphic lift. The cloud in Fig. 2 is a result of only the temperature contrast. This is because the cloud bases are well defined and the upper areas of the cloud are not so puffy. The cloud tops are cut off from entrainment bringing in dryer air. This stops the saturation from occurring.

4. Summary

The tall rapidly forming cumulus clouds can be related to a sudden increase in the lapse rate. The lapse rate increase came from a pool of dry air that came in with the frontal zone. The cooler air was filtrating into the region, but at the same time the sun was heating the surface at a fast rate. Normally, the sun would heat the surface and cause some rising of air. However, when this heating was combined with the cooler air aloft from the cold front, the lapse rate became almost dry adiabatic at the surface. This made the lower layer of the atmosphere absolutely unstable and supported deeper fair weather clouds to form. The lapse rate can be approximated by the formula

$$\Gamma = \left(-\frac{dT}{dz}\right) \tag{3}$$

where dT is the temperature change between two height levels in the atmosphere and dz is the distance between them. At 12Z on March 27th, the lapse rate was approximately 6°C/km in the lowest kilometer of the atmosphere. This is close to the moist adiabatic lapse rate of -6.5°C/km. This is an indication that the air was very saturated as the front was about to pass through State College. By 00Z on March 28th, the lapse rate had increased to approximately -10°C/km in the lowest kilometer of the atmosphere. This is close to the dry adiabatic lapse rate of -9.8°C/km. The change in the lapse rate is shown on the Skew-T diagrams in Fig. **??** and Fig. **??**.

The clouds had little to do with the actual low pressure system that passed through earlier. Well after a cold front passes, negative vorticity advection and height rises occur. At the time of the clouds, the front had just gone through seven hours ago. Upper level energy will often lag behind a cold front. However, since this cold front was so weak, there was little energy for the clouds to extract from. By the time the clouds were taken, the front had cleared the area and skies should have been clear. The reason for the cloud formations was the contrast between the cold air that arrived as a result of the front and the warming that was occurring at the surface. On nice days, heating normally causes the formation of small fair weather cumulus clouds with small lifetimes. With the enhanced temperature contrast, the clouds were able to grow significantly. Oragraphic lifting began to play a role in the cloud formations as the cold front directed the wind into the mountain. Parcels were forced upward at a faster rate and reached the LCL. In conclusion, the clouds came from a simple temperature contrast that formed after the cold front passed through the region and the frontal winds

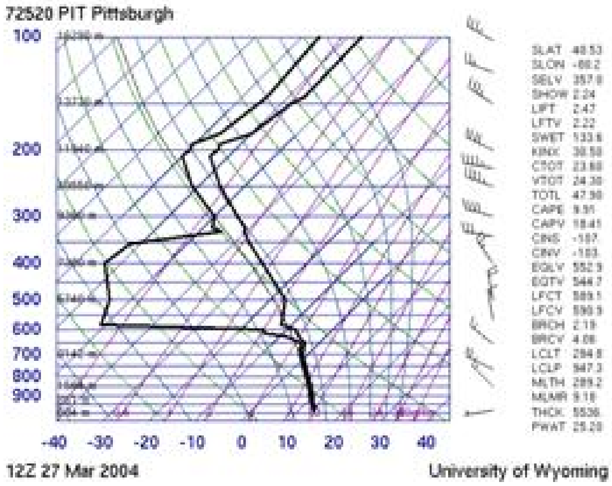

FIG. 11. Skew-T diagram for Pittsburgh on March 27th, 2004 at 12Z.

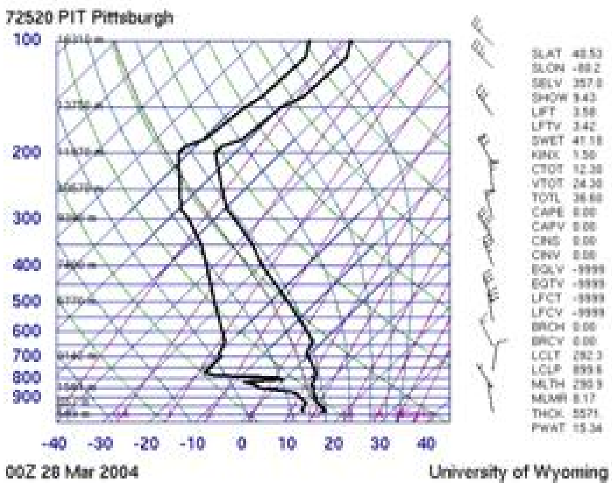

FIG. 12. Skew-T diagram for Pittsburgh on March 28th, 2004 at 00Z.

allowed significant lifting to occur.

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