If hot air rises, why is it cold in the mountains?

A laboratory experiment from the Little Shop of Physics at Colorado State University

CMMAP

Reach for the sky.

Overview

If you warm the air inside a balloon, the balloon will rise. But the temperature profile of the atmosphere shows that, near the earth, the air temperature drops as we go to higher elevations. Why doesn't the hot air end up at these higher elevations?

Theory

Here is the simple answer to the question of the previous paragraph: It does.

When a parcel of air warms up near the surface of the earth, it *will* rise. But as it rises, it moves into regions of lower pressure. The pressure of the atmosphere drops with altitude, by about 10 kPa (100 millibar) per 1000 m.

As a rising parcel of air moves into regions of lower pressure, it expands. And as it expands, it cools. The air has to do work to expand, and so its temperature must decrease—the only possible source of energy for the work of the expansion is the thermal energy of the gas. For the large air masses that move in the atmosphere, this is an **adiabatic expansion**—no thermal energy is transferred from adjacent air.

Watching the temperature change as the air expands.

You can show that a rising parcel of dry air will cool by about 10°C for each 1000 m that it rises. This is the *dry adiabatic lapse rate*. A parcel of hot air will rise—but it cools as it does so. The air temperature will still be lower at higher elevations.

A measurement of the actual change in temperature with height in the atmosphere is the *environmental lapse rate*. This can vary, but a typical value, for the "standard atmosphere" is 6.5°C of cooling for a 1000 m rise in elevation. You can see that this is less than the cooling a rising parcel of air will experience. So a parcel of hot air will rise to a cer-

tain point, and then stop. When you heat up a hot air balloon, it becomes buoyant, but, as it rises, it cools, and so it only rises so far—unless you add more heat.

The case of a hot air balloon makes a nice energy transformation problem because you are exchanging thermal energy of the gas in the balloon for potential energy of the balloon and its cargo. The hot air balloon is, in some sense, a heat engine!

The actual atmosphere is more complicated, because moisture plays a role. As the air cools, water vapor can condense, giving up latent heat. This is something we will deal with in another experiment. For now, it's time to get to work!

Doing the Experiment

This is a pretty straightforward experiment. You can get numbers from your instruments, but it's hard to do anything too significant with them because the expansion isn't adiabatic and isn't reversible. But you get a dramatic temperature change, which is easy to show.

> **SAFETY NOTE I: The bottles will easily hold more pressure than the pump can provide as long as they are intact. If a bottle has a defect, though, it may not hold. If a bottle has any defect, replace it.**

> **SAFETY NOTE II: When you pump the bottles up, they won't explode, but the caps can fly off at high speed if they are released. You should fasten the caps in place to eliminate this possibility. This isn't a big deal—folks open soda bottles all the time with no ill effects. But these bottle caps have valves in them so a bit of caution is warranted.**

The experiment goes like this:

- Pump up the bottle to a fixed pressure—about 2 bar is plenty. The air in the bottle will warm as you do this. Students can easily feel where the energy comes from for this increase in thermal energy!
- Let the bottle cool to room temperature.
- Let the air out of the valve, and notice the resulting cooling.

It's this last bit that is the crucial piece: As the air moves to lower pressure, it cools. Dramatically. A question to ask your students:

> **Where does the thermal energy go as the air in the bottle cools?**

The work done in the expansion isn't as obvious as the work done in compressing the gas, but it is no less real! The air must push back the atmosphere as it escapes, and the energy to do this must come from somewhere—the thermal energy of the air in the bottle.

Summing Up

This experiment is largely qualitative, but it does make a key point about energy transformations in air, one with good connections to the science of the atmosphere.

A final thought: Here's another way to think about the cooling with altitude: Thermal energy of a gas is due to the motion of the gas molecules. Suppose you aimed a particle straight up. It would rise, losing kinetic energy as it did so. So a parcel of such molecules would cool as it rose, as the speed of the molecules decreased!
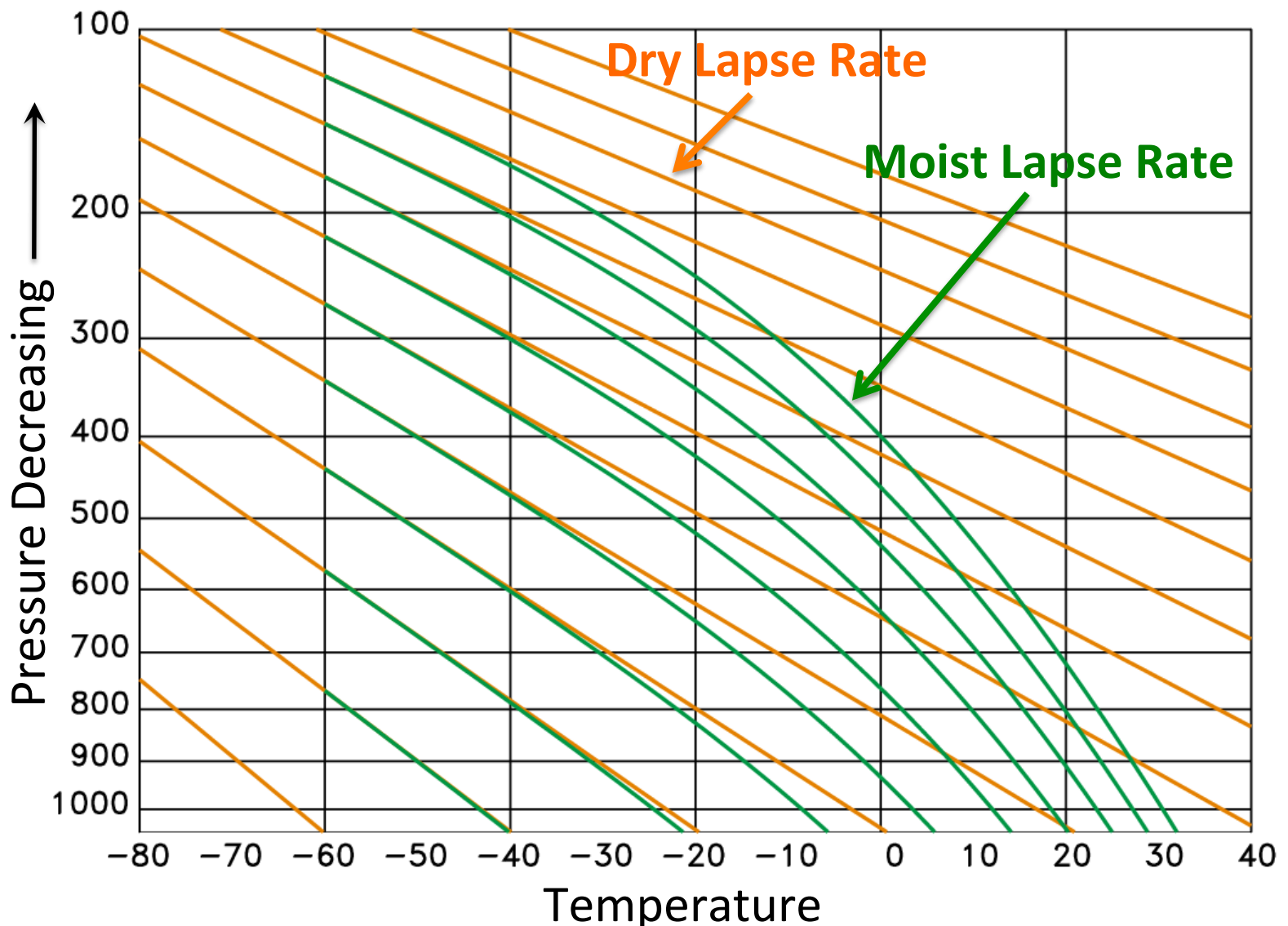
For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

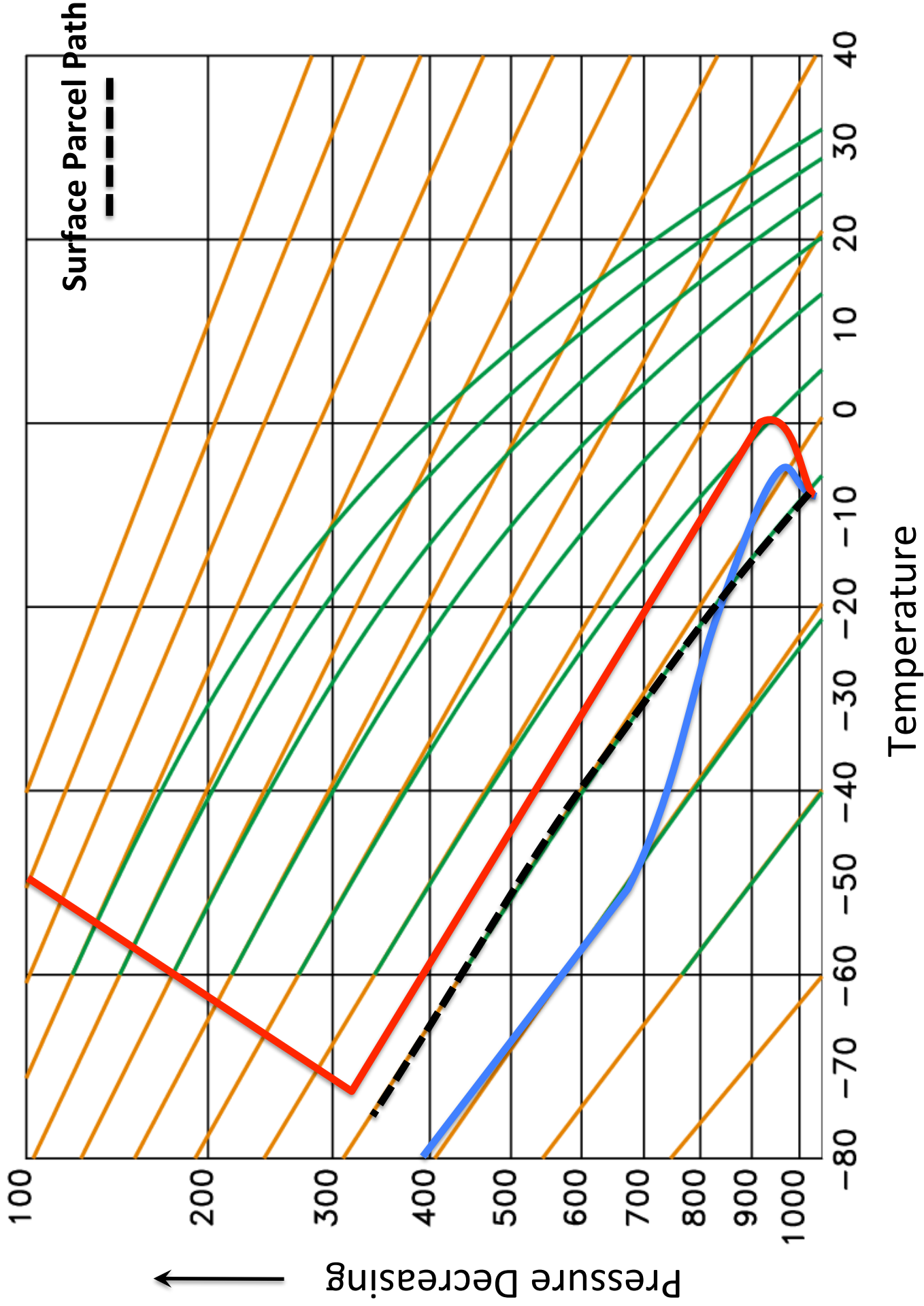# Determining Stability from Profiles of Temperature and Humidity

- Parcel follows dry lapse rate line if unsaturated ("dry")
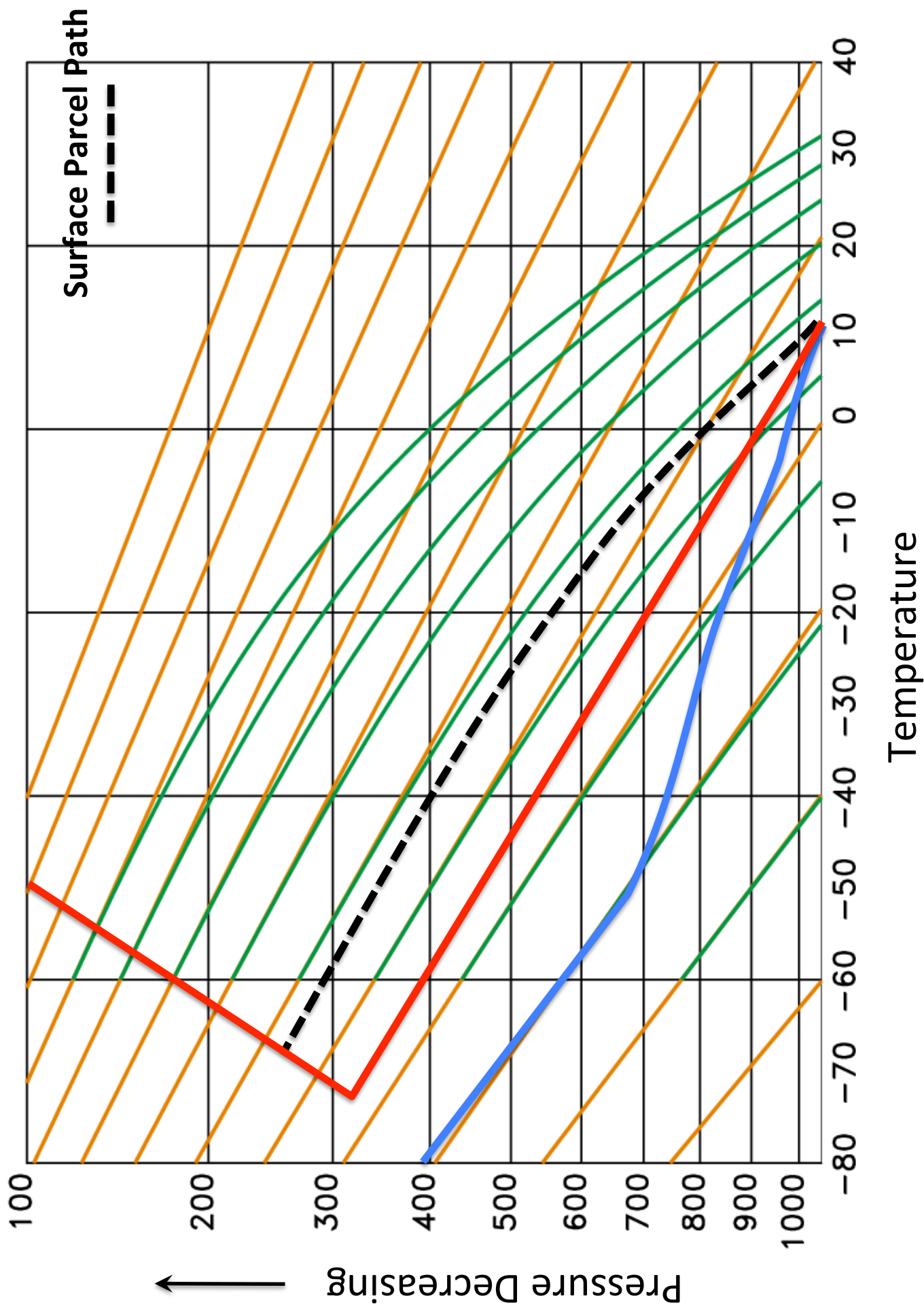- Follows moist lapse rate line if saturated ("moist")

Exercise

Directions: Fill in the areas between the curves (T_{REAL} and Parcel Path) with either red or blue, depending on whether it is positive or negative buoyancy (respectively). Then match the profiles to the pictures.
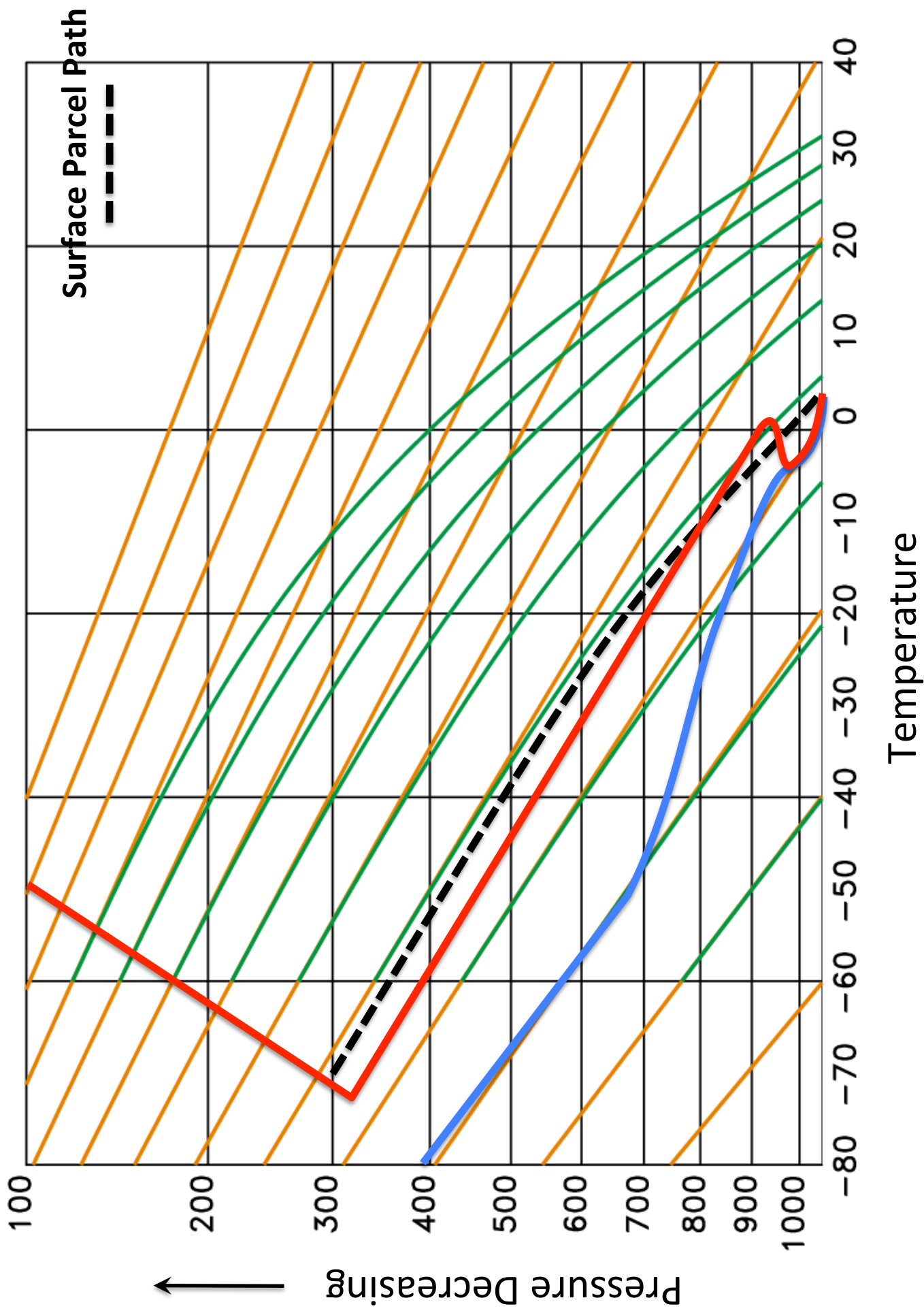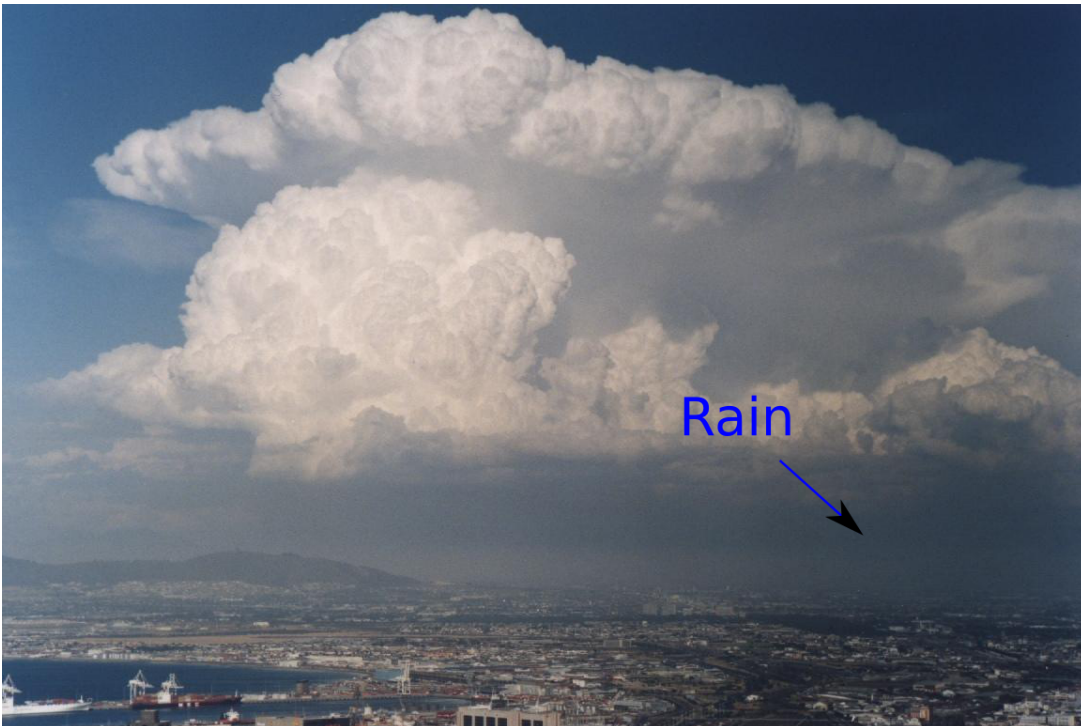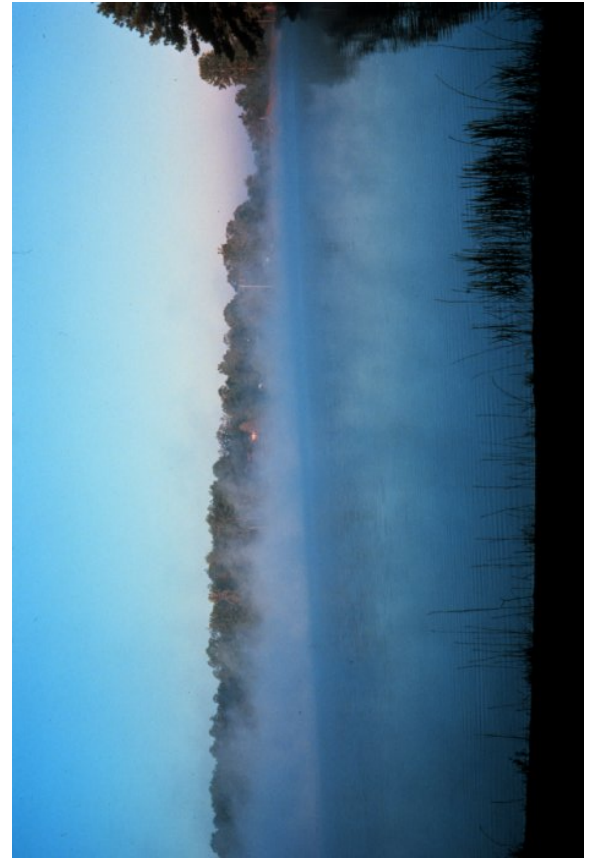
Exercise Profile 1

Surface Parcel Path - - -

Temperature

Pressure Decreasing ←

100
200
300
400
500
600
700
800
900
1000

40   30   20   10   0   -10   -20   -30   -40   -50   -60   -70   -80

Exercise Profile 2

Surface Parcel Path ---

Pressure Decreasing ←

100
200
300
400
500
600
700
800
900
1000

Temperature

-80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40

Exercise Profile 3

Surface Parcel Path

Pressure Decreasing

Temperature

Exercise Photos

A

B

C

Rain