The Effect of Lapse Rate on Atmospheric Stability

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Introduction

Atmospheric stability influences parcel motion in the atmosphere and affects whether an ascending air parcel will continue to rise or whether it will fall. In a stable atmosphere, an ascending air parcel tends to sink; in an unstable atmosphere, an ascending air parcel tends to rise. In a conditionally unstable atmosphere, a parcel may change from being stable to unstable or vice versa [1]. In the real atmosphere, stable conditions occur most commonly at night when there is little or no wind. Unstable conditions generally develop on sunny days due to strong insolation, which heats air at the surface, and when there is little wind, which otherwise facilitates atmospheric mixing. Understanding and modeling atmospheric stability is important for several reasons [2]. For example, the movement of air parcels (e.g., circulation and turbulent) can affect the safety of sea and air transportation.

The lapse rate Γ, the temperature change with height, is the defining characteristic of atmospheric stability. The standard atmospheric lapse rate is 6.5˚/km. Figure 1 shows the unsaturated adiabatic lapse rate Γ_{dry}, the saturated adiabatic lapse rate Γ_{sat}, and the classifications of atmospheric stability. For a given change in altitude when the atmospheric lapse rate Γ_{env} is greater than the unsaturated adiabatic lapse rate Γ_{dry} (10˚/km), the atmosphere cools more rapidly than the ascending parcel, and the parcel will continue to rise due to the upward buoyancy force [1]. This atmosphere is defined as absolutely unstable. For a similar change in altitude when the atmospheric lapse rate Γ_{env} is less than the saturated adiabatic lapse rate Γ_{sat} (6-7˚/km), the atmosphere cools more slowly than the ascending parcel, and the parcel will sink due to the net downward buoyancy force. This atmosphere is defined as absolutely stable.

The atmosphere is conditionally unstable when $\Gamma_{sat} < \Gamma_{env} < \Gamma_{dry}$. An ascending parcel in this regime may be stable or unstable depending on the parcel water vapor content. If the parcel contains sufficient water vapor, it will reach saturation (i.e., relative humidity = 100 percent) during its ascent, and liquid water will condense. Latent heat released by condensation heats the parcel and increases the buoyancy force on the parcel. [3] As a result, the parcel will continue to rise and is defined as unstable. If an ascending parcel does not contain sufficient water vapor to reach saturation, it will descend due to the downward buoyancy force and is defined as stable [1].

In this analysis, the lapse rate of the atmosphere is varied to produce an absolutely stable, conditionally unstable and absolutely unstable atmosphere, and parcel behavior therein is examined.

Model Description

The model used in this study is a parcel model consisting of an atmosphere and an air parcel. Consider an air parcel in thermal equilibrium with the surrounding atmosphere—the net force acting on such a parcel is zero. The force balance on the parcel is given by the hydrostatic equilibrium equation:

$$0 = -g - \frac{1}{\rho}\frac{\partial p}{\partial z}$$

where g is the gravitational constant, ρ is the density of air, and ∂p/∂z is the change in pressure with respect to height. The parcel model solves the hydrostatic equilibrium equation for some initial parcel motion. From Newton's second law of motion, the acceleration of the parcel must equal the sum of the gravitational and pressure gradient forces, which are given in the above equation. Because ∂p/∂z = -ρg, the acceleration of the parcel du′/dt is

$$\frac{du'}{dt} = g\frac{(\rho - \rho')}{\rho'}$$

where ρ′ is the density of the parcel and ρ is the density of the atmosphere. The right hand side of the above equation is the buoyancy force acting on a parcel. A parcel will ascend when it is less dense than its surroundings. Therefore, in solving the hydrostatic buoyancy equation, the model calculates intermittently the parcel temperature and density, and thus determines whether the parcel will ascend or descend.

The model permits the variance of several atmospheric parameters. In this study the lapse rate is varied to produce an absolutely unstable (Γ_{env} = 10.5˚/km), conditionally unstable (Γ_{env} = 6.5˚/km), and absolutely stable (Γ_{env} = 4˚/km) atmosphere. Once set, the atmosphere does not change from its respective regime. For the conditionally unstable atmosphere, the parcel water vapor mixing ratio w_v is set to 10^{-3} kg/kg and 10^{-2} kg/kg to produce a stable and unstable parcel, respectively. Γ and w_v are the only parameters changed in the parcel model code. The atmospheric lapse rate affects the behavior of parcel ascension so different parcel behavior—for example, in the rate of ascent and maximum height reached—is expected for different values of Γ.

Results and Discussion

Γ_{atm} = 4˚/km is chosen for absolute stability because it is less than the saturated adiabat (6-7˚/km). Γ_{atm} = 10.5˚/km is chosen for absolute instability because it exceeds the dry adiabat (10˚/km). Γ_{atm} = 6.5˚/km is chosen for conditional instability because it is greater than the saturated adiabat and less than the dry adiabat.

Figure 2 shows parcel motion in an absolutely stable atmosphere with Γ_{atm} = 4˚/km. The point at which the parcel and atmosphere reach thermal equilibrium is called the Level of Neutral Buoyancy (LNB). The parcel reaches the LNB at an altitude of ~0.2 km and continues to rise due to lifting momentum. The kink in the black curve marks the Lifting Condensation Level (LCL), the level at which the parcel becomes saturated and beings to ascend along the saturated adiabat. When saturated, water vapor condenses, releasing latent heat in the parcel, which decreases the cooling rate of the parcel. Though latent heat is released in the parcel, cooling due to parcel expansion dominates and upward displacement is restricted because of the downward (restoring) buoyancy force.

On the other hand, in an absolutely unstable atmosphere, the ascending parcel cools slower than the atmosphere, its upward displacement is unrestricted, and it continues to rise. Figure 3 shows parcel motion in an absolutely unstable atmosphere with Γ_{atm} = 10.5˚/km. The unstable parcel reaches the LCL, after which point latent heat from condensation and the buoyant force propel it upward. An LNB was not observed. In the real atmosphere, temperature inversions restricted ascension.

In a conditionally unstable atmosphere, the parcel water vapor content affects parcel stability. A parcel is stable as long as it remains unsaturated; conversely, it is unstable if it becomes saturated during its ascent. A stable and unstable parcel were created in the model by setting the mixing ratio w_v to 10^{-3} kg/kg and 10^{-2} kg/kg, respectively.

Figure 4 shows the motion of an unstable parcel in a conditionally unstable atmosphere with Γ_{atm} = 6.5˚/km. The unstable parcel contains sufficient water vapor to saturate. Saturation occurs at the

LCL and condensation releases latent heat, causing the parcel to cool more slowly. The unstable parcel ascends to a higher altitude than the stable parcel before reaching the LNB at ~1.3 km.

Figure 5 shows the motion of a stable parcel in a conditionally unstable atmosphere with Γ_{atm} = 6.5˚/km. The ascending stable parcel does not contain sufficient water vapor to saturate and consequently condensation does not occur. After reaching the LNB at ~0.3 km, it returns to its initial altitude due to the downward (restoring) buoyancy force. Figure 6 shows the water vapor mixing ratio as a function of altitude. Liquid water condenses out of the unstable parcel only. In addition to condensation, in the real atmosphere the amount of liquid water and water vapor in a saturated parcel decreases due to entrainment. Though the elementary parcel model does not account for entrainment, Figures 4 and 5 illustrate the dependence of parcel stability on parcel water vapor content.

Assumptions and Limitations of the Model

It is critical to understand the limitations of the model in order to interpret the model outputs correctly. The parcel model contains four primary simplifying assumptions that limit model accuracy—namely that the parcel retains its identity and does not mix with its environment; that the parcel motion does not disturb the environment; that the parcel pressure adjusts instantaneously to the ambient pressure of the fluid surrounding the parcel; and lastly, that the parcel moves isentropically, so that its potential temperature θ' remains constant.

In the real atmosphere, as a buoyant parcel ascends, mixing (entrainment) occurs and the parcel necessarily disturbs its surroundings as it and the atmosphere trend toward thermal equilibrium. However, the fraction of the parcel that mixes with the surrounding environment is small and thus the parcel retains its identity more or less. Though the parcel does not adjust *instantaneously* to the ambient pressure, it does so quickly. Lastly, the parcel does not move adiabatically—due to entrainment and heat transfer across the parcel boundary layer, net heat is either lost or gained during ascension. However, the fraction of heat lost through the parcel boundary layer is small relative to the total energy of the parcel. Though these four assumptions simplify the model and affect model accuracy, they do not render the model invalid or significantly inaccurate. Therefore, general trends observed in the results are valid.

Conclusion

The atmospheric lapse rate and water vapor mixing ratio were varied in an elementary parcel model to examine the three classifications of atmospheric stability. All other atmospheric parameters were held constant. Model outputs were considered with respect to model limitations. In the absolutely stable atmosphere, the parcel reached the LNB at ~0.2 km. In the absolutely unstable atmosphere, parcel ascension was not restricted and the LNB was not observed. A parcel with sufficient water vapor in a conditionally unstable atmosphere became unstable after it reached saturation, and it ascended to ~1.4 km. A dry parcel in the same regime was stable throughout its ascent due to a lack of latent heat, and ascended to ~0.6 km. Though the parcel model used in this study is elementary, it provides an accurate framework to understand the mechanisms at work in the real atmosphere, namely the effects of expansion, compression, and condensation on buoyancy forces.

References

[1] Curry, Judith A., and Peter J. Webster. Thermodynamics of Atmospheres and Oceans. New York, NY, Academic, 2005.

[2] Yosemite EPA, APTI Virtual Classroom, SI 409 - Lesson 4: Vertical Motion and Atmospheric Stability

[3] Smith, Roger K. The Physics and Parameterization of Moist Atmospheric Convection. Dordrecht, the Netherlands. 1997.

Figures

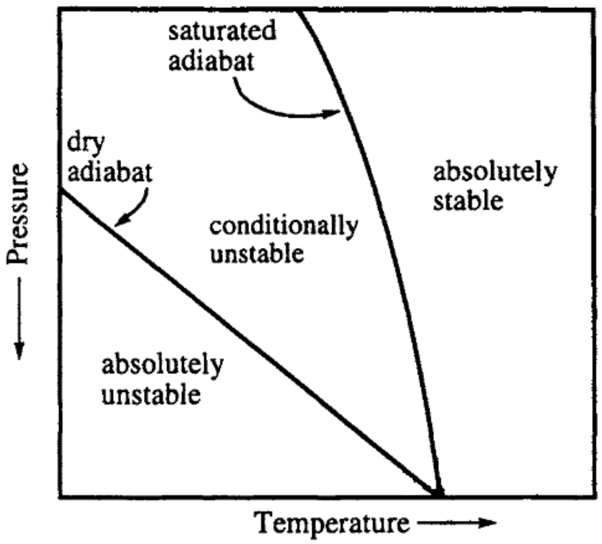

Figure 1: Regions of stability, instability and conditional instability. Figure is taken from Curry and Webster [1] with modifications.

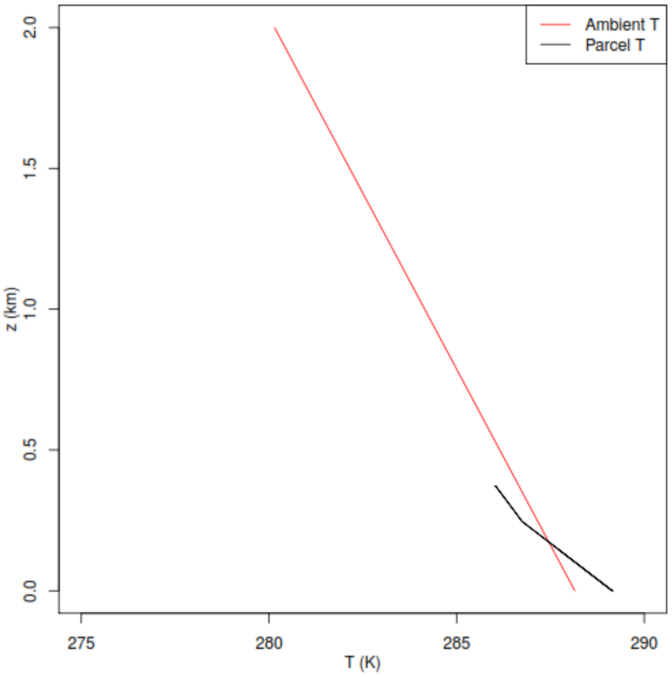

Figure 2: The change in ambient and parcel temperature between 0 - 2km altitude range for a lapse rate of 4˚/km.

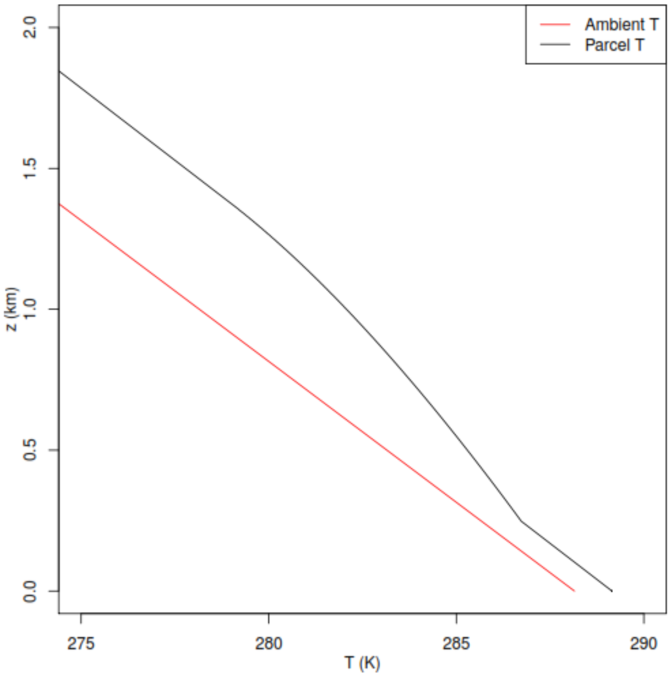

Figure 3: The change in ambient and parcel temperature between 0 - 2km altitude range for a lapse rate of 10.5°/km.

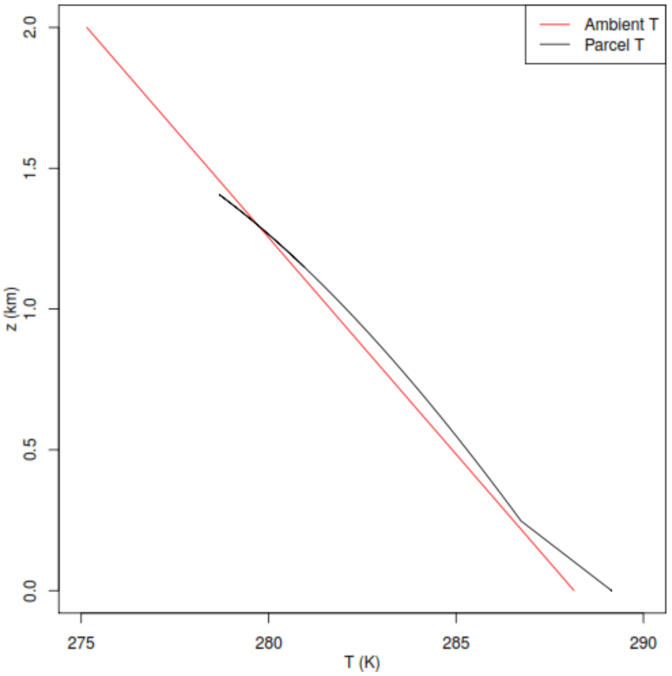

Figure 4: The change in ambient and parcel temperature between 0 - 2km altitude range for a lapse rate of 6.5°/km and with a water vapor mixing ratio of 10^{-2} kg/kg.

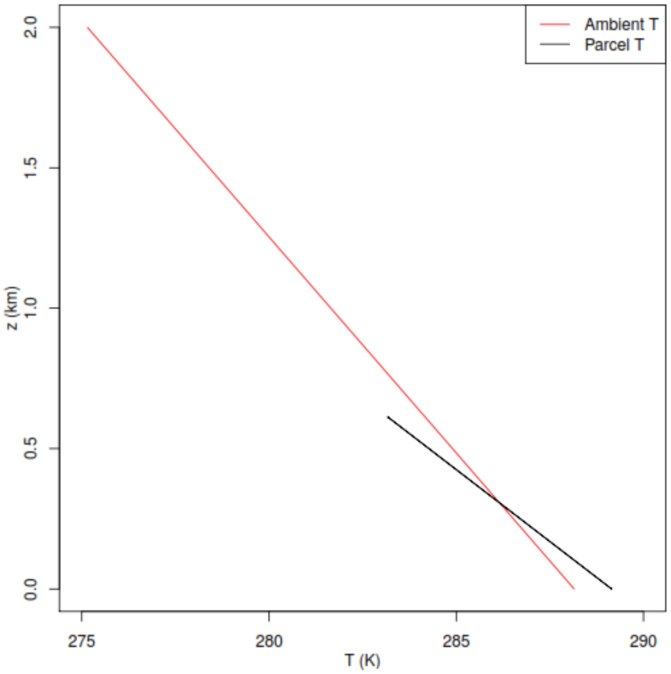

Figure 5: The change in ambient and parcel temperature between 0 - 2km altitude range for a lapse rate of 6.5°/km and with a water vapor mixing ratio of 10^{-3} kg/kg.