The effect of entrainment on air parcel convection

Introduction

Convection in the atmosphere occurs as a result of parcel-environment instability, or density differences, in the atmosphere. This instability is caused by solar radiation heating the Earth's surface creating warmer, less dense air which rises in the atmosphere until it becomes neutrally buoyant with the surrounding air. As an air parcel rises, it interacts with the surrounding air, mixing some of the ambient air into the air parcel. This process is called entrainment and affects both the heat content and liquid and vapor water content of a rising air parcel.

High entrainment rates inhibit deep convection by mixing the parcel with the environment, preventing the parcel from ascending to higher altitudes. Low entrainment rates have the opposite effect: the less ambient air entrained into a parcel, the higher it can ascend in the atmosphere before reaching neutral buoyancy. When a rising air parcel entrains relatively dry ambient air, the water vapor mixing ratio of the parcel decreases. This process is particularly important in clouds as entrainment of relatively dry environmental air into a cloud lowers the liquid water content substantially below what is expected in closed adiabatic ascent. For an air parcel entraining ambient air that is relatively moist, this will increase the water vapor mixing ratio of the air parcel. Understanding how entrainment rates influence convective processes is important because the entrainment rate in clouds is one of the most sensitive variables causing uncertainty in climate models (Knight et al. 2007).

Model

The simplest version of the parcel modeling approach uses four key assumptions: 1) The parcel retains its identity and does not mix with the surrounding environment; 2) the parcel motion does not disturb the surrounding environment; 3) the parcel and the environment are in mechanical equilibrium; 4) the parcel motion is isentropic, so that its potential temperature remains constant (Curry and Webster 1999). By including entrainment in the model we have abandoned the first assumption that a rising air parcel is a closed system. For short timescales, the effects of the air parcel on its surrounding environment can be ignored. The third assumption of equal pressure in the parcel and its surroundings is almost always true in the atmosphere. The fourth assumption is based on the assertion that if the parcel rises quickly, there will be little heat exchange. In addition to these basic assumptions, the model with entrainment also includes several additional assumptions. Water that condenses within the parcel does not precipitate out but adds to the parcel liquid water mixing ratio. Also, we assumed homogeneous entrainment which means that air is entrained homogeneously across the width of the air parcel and that the parcel becomes immediately homogeneously mixed (Pruppacher and Klett 2010). This homogeneous entrainment model is simplified but is adequate for our purpose of demonstrating microphysical behavior. Finally, we assume that entrainment rate is constant throughout the parcel motion.

To include the turbulent entrainment of momentum to the cloud model, it is necessary to add a drag force term to the buoyancy equation so that the equation becomes:

$$\frac{dW}{dt} = g\left(\frac{T-T'}{T'} - w_L\right) - \mu W^2 \qquad 1)$$

where W is the vertical velocity of the parcel (m s^{-1}), g is gravity (m s^{-2}), T is the parcel temperature (ºK), T' is the ambient air temperature, w_L is the parcel liquid water mixing ratio, and μ is the entrainment rate (m^{-1}) and has the form

$$\mu \equiv \frac{1}{m}\frac{dm}{dz} = \frac{1}{l} \qquad 2)$$

where *l* is the length scale that characterizes the mixing process (Pruppacher and Klett 2010). We chose entrainment rates of 5 $x10^{-4}$ m^{-1}, and 5 $x10^{-5}$ m^{-1}, representing mixing scales of 2 km and 20 km respectively. Cloud sizes vary greatly, but individual cloud sizes are usually on the order of 1 km wide. Therefore an entrainment rate corresponding to a mixing scale of 2 km can be thought of as an approximate representation of an average sized cloud, while a mixing scale of 20 km represents an unusually large cloud or a small cloud system. Clouds can occur on scales less than 2 km, however our model was dysfunctional with entrainment rates corresponding to scales less than 2 km. Therefore, our analysis of air parcel behavior is limited to air parcels with mixing scales of 2 km or greater. However, we can extrapolate our results to infer the behavior of smaller air parcels with higher entrainment rates.

It is also necessary to add an entrainment condensation function to the model which decreases the water vapor in the parcel due to entrainment with the dryer environmental air. If the parcel cools enough to become saturated, the parcel lapse rate will decrease because of the latent heat released from condensing water in the parcel. The warming from the latent heat will slow the decrease in temperature due to the decrease in pressure. Furthermore, entrainment will cause the parcel's water vapor mixing ratio to change. As the parcel moves vertically the rate of change of its water vapor mixing ratio will vary according to the following equation (Pruppacher and Klett 2010):

$$\frac{dw_v}{dt} = -\frac{dw_L}{dt} - \mu(w_v - w_v' + w_L)|W| \qquad 3)$$

In our simulations we consider a US standard atmosphere (lapse rate of 6.5 °K km^{-1}) at eighty percent saturation. For all our simulations the parcel starts with the same temperature (289.15 °K) and has the same lapse rate initially. The initial water vapor mixing ratios for the dry and moist parcel are 0 g kg^{-1} and .01 g kg^{-1} respectively.

Results

Figure 1A) shows the effect of the varying entrainment rates on the parcel temperature as it rises. It is subtle, but there is a greater decrease in temperature as the parcel rises (i.e. larger lapse rate) when there is a higher entrainment rate (μ= 5 $x10^{-4}$ m^{-1}). The lapse rate is not adiabatic when there is entrainment due to the temperature difference between the parcel and the environment (Fig. 1B). The parcel rises and temperature decreases due to the decrease in pressure, but also because it is mixing with the cooler environmental air. Once the parcel passes the level of neutral buoyancy it continues to rise because of the momentum it has acquired. After it reaches its maximum height it begins to fall (hence we observe two lapse rates for a given height). The water vapor mixing ratio of the dry parcel increased because of entrainment of relatively moist environmental air (Fig.1C). The water vapor mixing ratio continued to increase as the parcel descended because the parcel continued to mix with the ambient air during its descent. The liquid water mixing ratio is zero at all altitudes for a dry parcel with entrainment because the water vapor mixing ratio does not reach the saturation water vapor mixing ratio and therefore no liquid water can condense (Fig. 1D).

For a moist air parcel, the same entrainment rates had a much larger influence on the parcel processes and its path. The cooling of a parcel during its ascent decreased the saturation mixing ratio (Fig. 2C) eventually causing the parcel to become saturated even though water vapor mixing ratio decreased as a result of entrainment. Once saturated, the energy from the latent heat due to condensation decreased the lapse rate of the parcel (Fig. 2A, B). It is easy to see the instant the parcels became saturated in figure 2B by the sudden decrease in lapse rate. The parcel with the highest entrainment rate saturated at a lower height because the increased entrainment caused the saturation water vapor mixing ratio to decrease faster. A lower entrainment rate produced more liquid water (Fig. 2D). With a smaller entrainment rate the parcel could rise higher in the atmosphere, further decreasing the saturation mixing ratio and condense more water. When the parcels with entrainment began to descend the lapse rate decreased because liquid water in the parcel evaporated (Fig. 2A, B). As the parcel descended, the warming due to compression was offset by the liquid evaporation. The parcels warmed gradually during descent causing the saturation mixing ratio to gradually increase. Since the saturation mixing ratio did not increase significantly during the parcel descent, the parcel remained saturated to a lower height (Fig 2B, D; μ= 5 x10^{-4} m^{-1}).

Conclusions

There was considerable agreement between the model results and our expectations. We observed that with entrainment the height reached by the air parcel is substantially less than without entrainment. Moreover, our simulations show an increased temperature gradient when entrainment is included. Larger entrainment rates resulted in parcel temperature and water vapor mixing ratio closer to ambient values.

Some shortcomings of the model arose directly from the assumptions. For instance we assumed a constant entrainment rate, but in reality as the parcel grows the entrainment rate should change. In addition to this, as the parcel grows instantaneous mixing appears to be physically unrealistic. It is also worth mentioning that the results only apply for a standard atmosphere where the ambient profile remains constant, hence situations where the atmosphere is not stable were not considered.

In light of the aforementioned assumptions, in future models we can address these unrealistic ideas and allow the entrainment rate to change with time. To further improve the model the parcel should have a volume that changes due to entrainment and reduced pressure with height. Instead of homogenous mixing across the parcel the edges of the parcel should be more prone to mixing. Finally, precipitation should be able to occur to allow for a more realistic parcel evolution. Improving the representation of entrainment in parcel convection models, together with improved measurements of entrainment rates in the atmosphere, is necessary to better constrain the role of entrainment in cloud convection. Cloud processes and distribution play an important role in climate on regional and global scales therefore increasing our understanding of cloud convective processes is essential to improve the predictive capabilities of climate models.

References

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Figures

Fig. 1 A) Temperature, B) Lapse rate, C) water vapor mixing ratio and D) liquid water mixing ratio of an ascending dry air parcel with varied entrainment rate as a function of altitude.

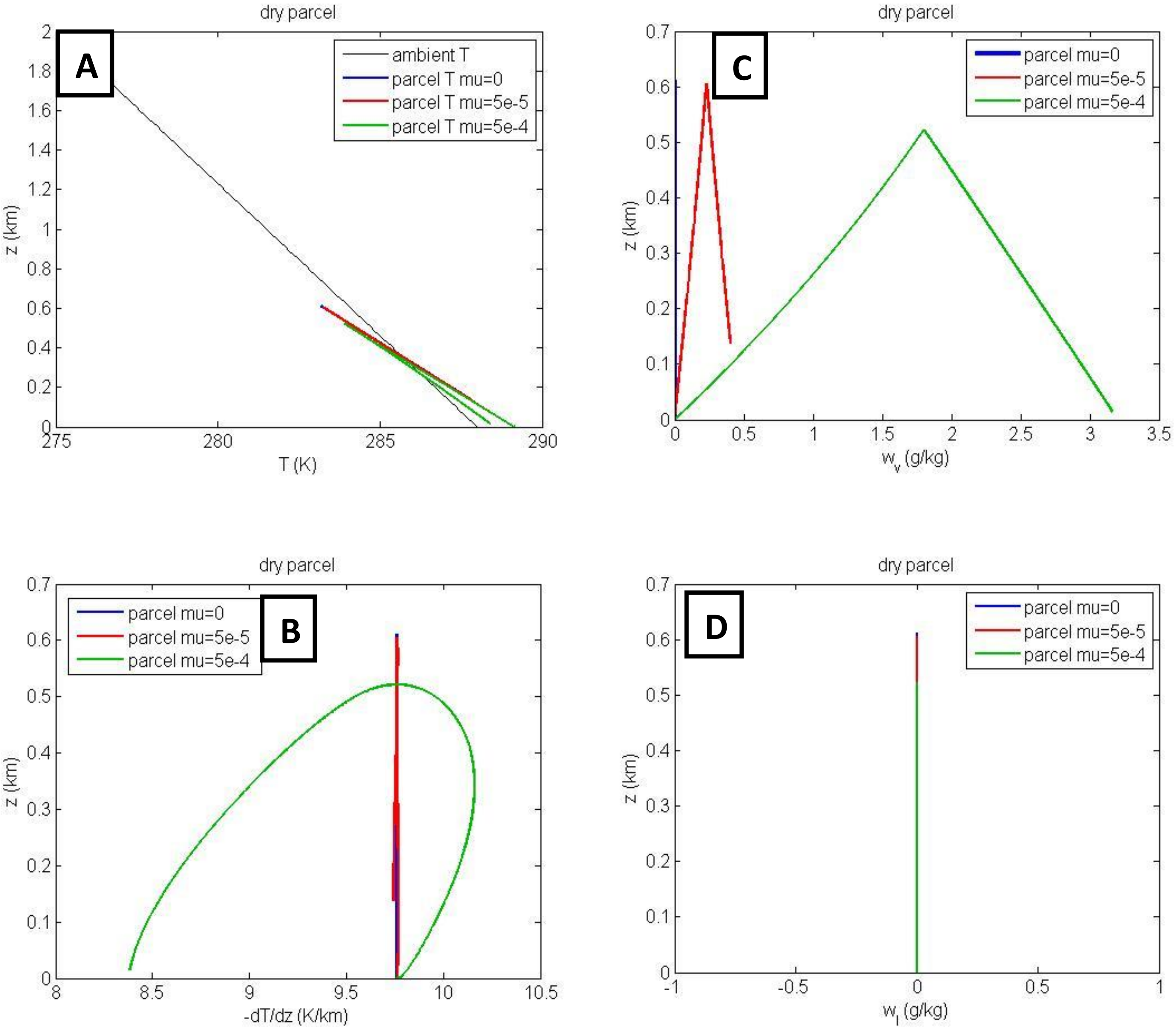

Fig. 2

A) Temperature, B) Lapse rate, C) water vapor mixing ratio and saturation water vapor mixing ratio and D) liquid water mixing ratio of an ascending moist air parcel with varied entrainment rate as a function of altitude.