# Comments on "Convective Available Potential Energy in the Environment of Oceanic and Continental Clouds"

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## 1. Introduction

Lucas et al. (1994a,b) pointed out that the strongest 10% of the oceanic updrafts have average vertical velocities exceeding 4–5 m $s^{-1}$ compared to values of 12–13 m $s^{-1}$ for continental updrafts. They suggested that it is time to focus on the issue of why upward velocities are higher in continental air and showed that there is no basis for attributing the vertical velocity difference to differences in convective available potential energy (CAPE) because CAPE is in the 1500–2500 J $kg^{-1}$ range in both cases. Updraft velocity generally increases with increased CAPE, but careful statistical analysis by LeMone et al. (1994) has shown that higher CAPE is not responsible for the higher vertical velocity over the continental areas. This note examines how condensation at low elevation and the resulting evaporative cooling could be responsible for the low updraft velocity over oceanic areas.

## 2. Virtual temperature of air mixtures

Figures 1 and 2 illustrate the fundamental difference between the mixing of ambient air into a parcel containing *no* liquid water and the mixing of ambient air into a parcel containing liquid water. In Fig. 1, the parcel is saturated but contains no condensed water. In Fig. 2, the parcel contains 2 g $kg^{-1}$ of liquid water in addition to being saturated. In both cases, the mixing process is adiabatic and takes place at a constant pressure of 90 kPa, the temperature of the ambient air is 290 K, and its relative humidity is 60%. The temperature of the saturated parcel is 290.5 K.

In the *no* liquid water case, Fig. 1, the virtual temperature of the mixture decreases linearly with increasing concentration of ambient air in the mixture. The solid horizontal line at 291.4 K is the virtual temperature of the environment, the zero-buoyancy level. The virtual temperature of the ambient air is 1.4 K higher than its actual temperature. The virtual temperature of the unmixed parcel is 2.4 K higher than its actual temperature and 1.5 K higher than the virtual temperature of the environment. The unmixed parcel has a buoyancy of 1.5 K. The virtual temperature of the mixture approaches the virtual temperature of the environment as the concentration of ambient air in the mixture approaches 100%, but the mixture remains positively buoyant even when it is 90% ambient air. The buoyancy of the 50–50 mixture is +0.75 K. Provided neither constituent contains condensed water, the virtual temperature of a 50–50 mixture is the average of the virtual temperature of the constituents irrespective of the relative humidity of either constituent.

In the liquid water case, Fig. 2, the virtual temperature of the mixture has a deep valley. The total relative humidity of the unmixed parcel, including its 2 g $kg^{-1}$ liquid water content, is 114%. The buoyancy of the unmixed parcel is 1 K. The buoyancy of the 50–50 mixture is 2 K lower than in the no liquid water case, −1.3 versus +0.75 K. The virtual temperature of the mixture is lower than the virtual temperature of either constituent. The evaporative cooling occurs during the initial dilution of the parcel, as the relative humidity is being reduced from 114% to 100%, while the condensed water is evaporating. Mixing as little as 20% of ambient air into the rising parcel is sufficient to reduce the buoyancy of the parcel to zero.

Surface relative humidity is significantly higher in oceanic air than in continental air. Surface relative humidity is typically 80%–90% for oceanic air and 60%–80% for continental air. The lifting condensation level decreases with increasing surface relative humidity and is typically 90–95 kPa for oceanic air and 75–85 kPa for continental air. Figures 1 and 2 could be representative of the mixing process at the 90-kPa level over continental and oceanic areas, respectively. Evaporative cooling comes into play starting at 500–1000 m for oceanic updrafts and starting at 1500–2500 m for continental updrafts.

Lucas et al. (1994a) pointed out that not only the upward velocity but also the diameter of the updrafts are larger over continents than over oceans. The di-

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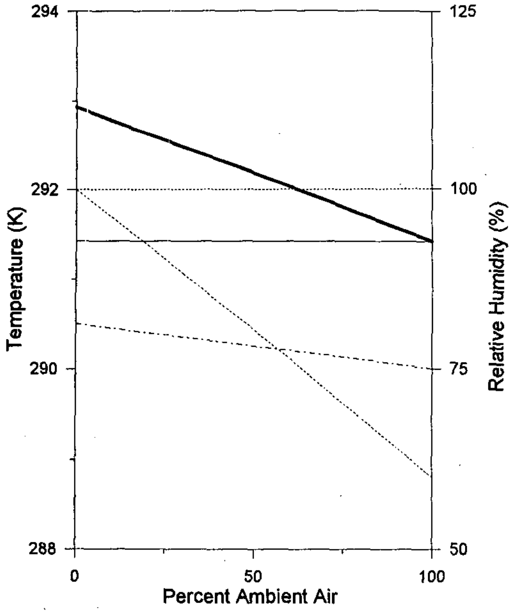

FIG. 1. Isenthalpic mixing of an air parcel with ambient air at 90 kPa. Horizontal axis is the percent ambient air in the mixture. Left vertical axis shows temperature and virtual temperature. Right vertical axis shows relative humidity. The ambient air at the right is at 290 K and has 60% relative humidity. The parcel on the left is at 290.5 K and has 100% relative humidity, and contains no condensed water. The heavy solid line shows the virtual temperature of the mixture, the light solid horizontal line the virtual temperature of ambient air, and the dot–dash line the actual temperature of the mixture. Dotted lines show the relative humidity of the mixture and 100% relative humidity.

ameters of the 10% strongest updrafts are in the 1.6–4-km range for oceanic areas and always greater than 4 km for continental areas. Up to the lifting condensation level, convective thermals can grow from entrainment without loss of buoyancy from evaporative cooling. Above the condensation level, evaporative cooling reduces buoyancy. Mixed updrafts are not a homogenous mixture, they contain mixtures of all concentrations. The positively buoyant mixtures tend to continue rising, and the negatively buoyant ones tend to separate and descend. The negatively buoyant mixtures that separate do not contribute to the growth of the updraft.

## 3. Calculation basis

Adiabatic mixing is a constant enthalpy process (Dufour and Van Mieghem 1975). The enthalpy of the mixture is equal to the sum of the enthalpy of the constituents, and the water content of the mixture is equal to the sum of the water content of the constituents. The actual temperature of the mixture was calculated using a solver. The virtual temperature was calculated from the actual temperature and the mixing ratio. The effect of evaporative cooling due to mixing was considered by Emanuel (1981) and Randall (1980).

The effect of evaporative cooling on buoyancy of the mixture is much larger than the effect of water loading. At 90 kPa, adding 1 g of liquid water to 1 kg of ambient air decreases the virtual temperature of the air by 0.3 K when the water does not evaporate, but decreases the virtual temperature by 2.2 K when the water evaporates. In Fig. 2, the double-dot line is the buoyancy of the mixture when the weight of the liquid water is neglected; the liquid water loading of 2 g $\mathrm{kg}^{-1}$ reduces the virtual temperature of the unmixed parcel by 0.5 K, from 292.9 to 292.4 K. The virtual temperature of the 50–50 mixture is 2 K lower in case 2 than in case 1 because the initial constituents contained 1 g of liquid water per kilogram of final mixture. Sensitivity analysis shows that the cooling is basically proportional to the initial liquid water content of the mixture. Figure 3 shows a case where the parcel contains 1 g $\mathrm{kg}^{-1}$ of liquid water and has zero-initial buoyancy; 1 g $\mathrm{kg}^{-1}$ is sufficient to reduce the buoyancy of the mixture by 1.4 K. The virtual temperature minimum occurs at lower concentration than in Fig. 2 because there is less water to evaporate. Sensitivity analysis shows that either decreasing the relative humidity of the environment or increasing the liquid water of the parcel increases evaporative cooling. There would be no evaporative cooling if the relative humidity of the environment were 100%.

According to Petterssen (1956, 146), Austin correlated the occurrence of cumulus showers with the lapse rate and with the relative humidity of the free atmosphere and found that high relative humidity aloft is at least as important as steep lapse rate. Austin calculated

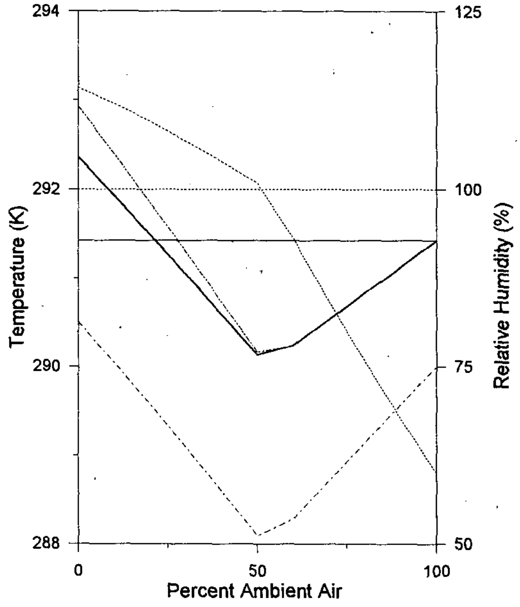

FIG. 2. As in Fig. 1 except parcel contains 2 g $\mathrm{kg}^{-1}$ liquid water. Double-dot line shows the virtual temperature of mixture without liquid loading.

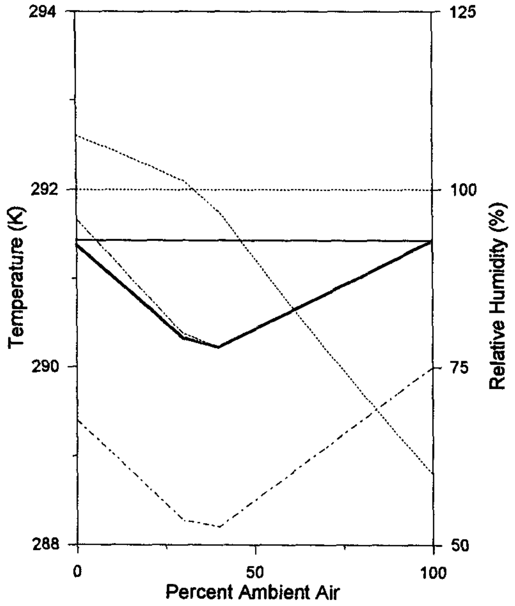

FIG. 3. As in Fig. 2 except parcel has a temperature of 289.4 and contains 1 g $kg^{-1}$ liquid water. The parcel and the environment initially have the same virtual temperature.

by how much entrainment reduces the temperature of rising air masses and showed that entrainment keeps the temperature of the updraft close to the temperature of the sounding. The evaporative cooling that can occur in dry air is very high and can explain why fair weather cumulus are shallow and why there is little deep convection in the subtropics. Austin's method is essentially equivalent to the one used in this comment. Austin calculated the height of cloud top by considering the effect of mixing. For case 2, mixing 20% ambient air reduces the buoyancy to zero. At the entrainment rate of 4% $kPa^{-1}$ used by Austin, the buoyancy of the parcel would be reduced to zero after rising 5–10 kPa, depending on the lapse rate, which is well below the level of neutral buoyancy for the unmixed parcel.

Austin demonstrated from statistical analysis of observational data that low humidity above the condensation level correlates with reduced precipitation. Lucas et al. (1994b) showed from statistical analysis of observational data that oceanic areas are associated with reduced updraft velocity and diameter. Austin explained how entrainment above the condensation level could reduce buoyancy and precipitation. This comment examines how high surface humidity and the resulting low condensation level could reduce updraft diameter and velocity. The upward velocities over oceanic areas are low both in the ITCZ where the humidity aloft is high and in the subtropics where the humidity aloft is low. The low upward velocities over oceanic areas, therefore, appear to be more closely associated with low condensation level than with low relative humidity above the condensation level. Ambient relative humidity as high as 60% may be low enough to keep the updraft diameter low when the condensation level is low.

## 4. Conclusions

Updraft velocities depend on CAPE, the work produced when a parcel from the surface rises to its level of neutral buoyancy, and on intermediate mixing processes that are not considered in CAPE calculations. The reason for the higher velocity of continental updrafts could be that the updrafts can rise to greater heights and grow to larger diameters before evaporative cooling comes into play. The reason for the lower velocity of oceanic updrafts could be that higher surface relative humidity bring about evaporative cooling at low level where it is not present in continental areas.

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