Reply

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Michaud (1996) points out that the height of the lifting condensation level can have a significant role in determining the size of clouds and, hence, the strength of their updrafts. In comparing marine and continental cumuli, the role is twofold. First, the shallower subcloud layer over water implies smaller eddies, which are more susceptible to entrainment, and second, the lower cloud base means a greater depth through which mixed-phase mixing (liquid and vapor) can rob the cloud of its buoyancy.

We also note the importance of the first mechanism in Lucas et al. (1994, p. 3191). If one assumes that the depth of the mixed layer is roughly equal to the depth of the subcloud layer, then Michaud's point and ours are nearly identical. We do not invoke any mechanism for an increase in subcloud eddy size with height; this has been noted in the boundary layer literature for decades. The cited Grossman (1982) and Kaimal et al. (1976) references are typical. In addition, if we note that the entire boundary layer is drawn into larger precipitating convective systems, the horizontal scale of that layer of air is the boundary layer depth (again, depth of subcloud layer, for a cumulus-topped PBL).

The second mechanism is an interesting idea to explain the differences in size and intensity of marine and continental cumulus. Its applicability to isolated cumulus is obvious. However, most of the drafts sampled in the work on convective cores (LeMone and Zipser 1980; Zipser and LeMone 1980; Jorgensen et al. 1985; Jorgensen and LeMone 1989; Lucas et al. 1994) were not in an *undisturbed* environment but rather were embedded in larger mesoscale convective systems. This means that, for the most part, the air entrained into the convective cores has been modified from the undisturbed environment. If the *modified* environment is saturated (or nearly so), the effects of evaporative cooling are reduced. Zipser and LeMone (1980, their Fig. 3) note that convective cores in the Global Atmospheric Research Program Atlantic Tropical Experiment appear to follow the same vertical scaling as plumes in the atmospheric boundary layer. This suggests that entrainment of lower theta-*e* air in a cloudy environment is analogous to entrainment of lower theta air in the clear air boundary layer.

This does not mean that Michaud's argument is necessarily invalid for these cores—even plumes in mesoscale convective systems are not entirely insulated from the environment, and a subset of the plumes sampled probably were exposed to environmental air even if not surrounded by it.

Upon considering Michaud's arguments, and reexamining the fundamental question of why convection is more vigorous over land, a number of issues became obvious to us that might enter into a more rigorous investigation of this hypothesis.

The importance of convective inhibition. Convective inhibition (CIN), or "negative area," is a measure of the energy needed by an air parcel in the boundary layer to overcome negative buoyancy and reach its level of free convection (Carlson 1991). Over the tropical oceans for soundings thought to be representative of the environment of deep convection, CIN values typically range from 5 to 10 J kg^{-1} (Barnes and Sieckmann 1984; Alexander and Young 1992; Griffith and Zipser 1993), while for nonsevere squall lines over Oklahoma the values are on the order of 70 J kg^{-1} (Bluestein et al. 1987). We speculate that the above results have generality; CIN over the continents is generally higher than over the tropical ocean, which means that parcels at and immediately above cloud base are negatively buoyant and thus must be accelerated upward primarily by dynamic processes. As a result, the flow is laminar, and little entrainment may occur below the level of free convection. Cloud pictures of strong thunderstorms and squall lines reveal that the lowest portions of the clouds often appear smooth, in line with the scenario described

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above. The end result is indeed similar to what Michaud proposes, but the reasons for updrafts over land surviving entrainment better must go beyond thermodynamics alone.

The droplet size differences in marine and continental clouds. As can be noted in any text on cloud physics (e.g., Fletcher 1962), the droplet size distribution of marine and continental cumuli are quite different. The droplet spectrum in marine cumuli tends to be composed of fewer, larger droplets. Over the continents, the droplet spectrum is narrow with high numbers of smaller droplets. By virtue of their smaller diameter, the droplets in continental clouds are quicker to evaporate. This consideration is probably a second-order effect. A more important consequence of the broad droplet spectrum is that marine clouds produce rain much more rapidly through coalescence. Therefore, for any given distance above cloud base, comparatively more *cloud* liquid water will remain with the updraft in land clouds. If availability of cloud water for evaporation is an important factor, it follows that the higher above cloud base the more liquid available over land. This effect would *increase* the effectiveness of entrainment in land clouds compared to ocean clouds, at least above the low troposphere; however, we suggest that availability of cloud liquid water for evaporation is not a major issue there.

The source of entrained air and the mixing mechanism. The mechanism of entrainment and the source of the entrained air are important in this consideration. Entrainment through the cloud top would mix air with different properties from entrainment through the sides. The review by Blyth (1993) on entrainment in cumulus clouds demonstrates the complexity of this issue. For small cumulus, the consensus is that the source of the entrained air is 1–2 km above the observation level. However, the specifics of the mixing process remain uncertain. Some studies suggest that cloud-edge downdrafts are driven more by dynamic forcing than by evaporative cooling. Others suggest that the mixing of momentum is responsible for penetrative downdrafts. Is this an important issue for our dataset? The details of how the mixing in these clouds is accomplished must be better understood, and a larger database of ''environmental'' soundings obtained, before the relative importance of entrainment to the question at hand (land vs water updraft speeds) can be determined.

The differences in the environmental humidity profiles over the ocean and the continent. Generally, climatology would suggest that the continental clouds would be growing in a drier environment. This would work to weaken continental clouds from Michaud's mechanism, although strong downdrafts that can result from evaporation would tend to force larger and more vigorous convective systems. We suggest that further work on this matter is in order before general statements can be made.

In summary, we agree with Michaud that the deeper boundary layer over land is a good starting point to seek the reasons for cumulus over land seeming to be more effectively sheltered from the deleterious effects of entrainment than cumulus over oceans. The specific mechanism Michaud invokes, availability of cloud water for evaporation, is worthy of attention in certain contexts but may not be as important to the dataset in question, which is concerned with cumulonimbus clouds rising through the depth of the troposphere, often embedded within mesoscale convective systems. Our brief and admittedly speculative list of the most important reasons is the following:

- The shape of the CAPE. As argued in Lucas et al. (1994), most tropical ocean soundings have large integrated values of convective available potential energy (CAPE) but relatively small values of buoyancy at any given level compared with many soundings over land, which often have large buoyancy in the middle troposphere. Once a cloud taps these large buoyancies, any entrainment mechanism is less likely to decelerate the updraft very effectively, nor will water loading be effective. As Lucas et al. (1994) note, water loading over land is of comparable magnitude to that over the ocean but is a smaller fraction of the total buoyancy in the middle troposphere, where the vertical velocity measurements are taken.
- Larger diameter eddies over land, related directly to the greater depth of the boundary layer, help shelter the updrafts from entrainment during their critical passage through the lower troposphere. We are in agreement with Michaud on this important point.
- Larger CIN over land, which means larger negative buoyancies are being overcome by land clouds in the low troposphere, which means that dynamic forcing is stronger over land. Dynamic lifting of large eddies through the negatively buoyant layer suggests a regime of laminar flow below the level of free convection, which is better protected from entrainment of environmental air.

REFERENCES

Alexander, G. D., and G. S. Young, 1992: The relationship between EMEX precipitation feature properties and their environmental characteristics. *Mon. Wea. Rev.*, **120**, 554–564.

Barnes, G. M., and K. Sieckman, 1984: The environment of fast- and slow-moving tropical mesoscale convective cloud lines. *Mon. Wea. Rev.*, **112**, 1782–1794.

Bluestein, H. B., G. T. Marx, and M. H. Jan, 1987: Formation of mesoscale lines of precipitation: Nonsevere squall lines in Oklahoma during the spring. *Mon. Wea. Rev.*, **115**, 2719–2727.

Blyth, A. M., 1993: Entrainment in cumulus clouds. *J. Appl. Meteor.*, **32**, 626–641.

Carlson, T. N., 1991: *Mid-latitude Weather Systems.* Harper Collins, 507 pp.

Fletcher, N. H., 1962: *The Physics of Rainclouds.* Cambridge Press, 386 pp.

Griffith, J. M., and E. J. Zipser, 1993: A comparison of the properties and surface fluxes associated with the inflow and downdraft air of tropical MCSs. *Proc. 20th Conf. on Hurricanes and Tropical Meteorology,* San Antonio, TX, Amer. Meteor. Soc., 209–212.

Grossman, R. L., 1982: An analysis of vertical velocity spectra obtained in the BOMEX fair-weather, trade-wind boundary layer. *Bound.-Layer Meteor.*, **23,** 323–357.

Jorgensen, D. P., and M. A. LeMone, 1989: Vertical velocity characteristics of oceanic convection. *J. Atmos. Sci.*, **46,** 621–640.

——, E. J. Zipser, and M. A. LeMone, 1985: Vertical motions in intense hurricanes. *J. Atmos. Sci.*, **42,** 839–856.

Kaimal, J. C., J. C. Wyngaard, D. A. Haugen, O. R. Cote, Y. Izumi, S. J. Caughey, and C. J. Readings, 1976: Turbulence structure in the convective boundary layer. *J. Atmos. Sci.*, **33,** 2152–2169.

LeMone M. A., and E. J. Zipser, 1980: Cumulonimbus vertical velocity events in GATE. Part I: Diameter, intensity and mass flux. *J. Atmos. Sci.*, **37,** 2444–2457.

Lucas, C., E. J. Zipser, and M. A. LeMone, 1994: Vertical velocity in oceanic convection off tropical Australia. *J. Atmos. Sci.*, **51,** 3183–3193.

Michaud, L. M., 1996: Comments on "Convective available potential energy in the environment of oceanic and continental clouds". *J. Atmos. Sci.*, **53,** 1209–1211.

Zipser, E. J., and M. A. LeMone, 1980: Cumulonimbus vertical velocity events in GATE. Part II: Synthesis and model core structure. *J. Atmos. Sci.*, **37,** 2458–2469.