Mixed Layer Moisture Structure

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ABSTRACT

Radiosonde data from the National Hail Research Experiment and the Wangara experiment are examined to study vertical gradients of moisture in heated boundary layers which are well-mixed in virtual potential temperature. The frequent occurrence of a significant decrease of moisture with height in the mixed layer over the high plains region of the United States seems to be related in part to rapid growth of the mixed layer into very dry air aloft and/or height variations of horizontal advection of moisture. However, the exact cause cannot be unambiguously determined from the data.

1. Introduction

The present study analyzes radiosonde data from the National Hail Research Experiment (NHRE) toward the goal of documenting the frequent occurrence and possible causes of vertical gradients of moisture in the mixed layer over the high plains of the United States. To date, mixed layer models as well as forecasting techniques for moist convection almost categorically neglect such structure.

2. Data analyses

We focus on the statistics of the mixed layer behavior. Individual radiosonde soundings are difficult to interpret in the convectively mixed layer since they represent instantaneous measurements and turbulent fluctuations may be large. For example, numerical simulation of Wangara day 33 (Deardorff, 1974) indicates that even under quite dry conditions ($q \approx 3$ g kg^{-1}) the standard deviation of specific humidity due to "turbulence" near the top of the mixed layer can be as large as 0.5 g kg^{-1}. The NHRE radiosondes (GMD-1) were released at Sterling, Colo., and four other locations in northeast Colorado and southwest Nebraska (Fig. 1) from late May to early August, 1972–74. Most of the analyses reported here are for Sterling which is the farthest from the Rocky Mountains of the two stations, Sterling and Grover, where radiosondes were regularly released at least four times daily. Statistics for Grover did not exhibit interesting differences from those of Sterling.

In most of the analyses, only days on which no clouds were observed between 0900 and 1400 (all times Mountain Standard), except for high thin scattered clouds, are considered. In this manner variations in surface heating are minimized and complications due to mixed layer-cloud interactions are excluded. Variations in growth statistics between completely clear days and days with reported high thin scattered clouds are found not to be important for this data set. For convenience we will refer to both types of days as clear days.

On 33 of the 35 days which satisfy the above criteria, a well-mixed layer can be defined from the potential temperature distribution. The usual marked decrease in specific humidity at the mixed layer top (maximum in gradient magnitude) is sometimes of assistance in determining the approximate location of the mixed layer top. Relative humidity profiles are often particularly useful in subjectively estimating mixed layer depths since relative humidity combines effects due to potential temperature increase and specific humidity decrease. The definition and determination of mixed layer depth seems reasonably clear from the composite profiles in Figs. 2 and 3, where potential temperature is roughly constant over a layer bounded by a superadiabatic layer at the bottom and an inversion at the top. The composite profiles are constructed by normalizing height with the mixed layer depth and normalizing specific humidity with its surface value for each individual day, and then averaging. Composite profiles are effective means of illustrating typical profiles of potential temperature and specific humidity since the vertical gradients of both at a given relative level in the mixed layer rarely change sign from day to day, at least for the geographic regions examined here. However, such profiles must be interpreted with caution since external influences such as horizontal advections are likely governed by depth scales different from the mixed layer depth. Due to the relatively low values of specific humidity and to the qualitative nature of the present study, it is not

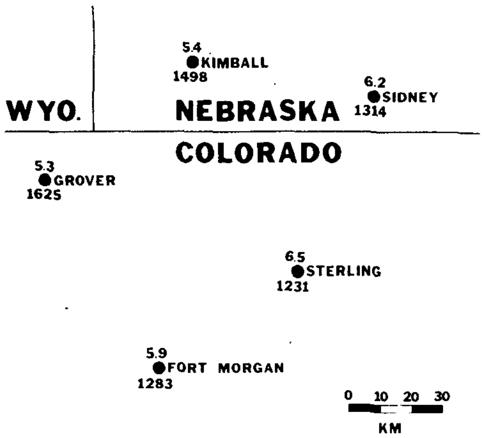

FIG. 1. Average summertime (15 May–10 August) 1400 MST mixing ratio (g kg^{-1}) in the lowest 100 mb, 1972–74. Station elevations are in meters.

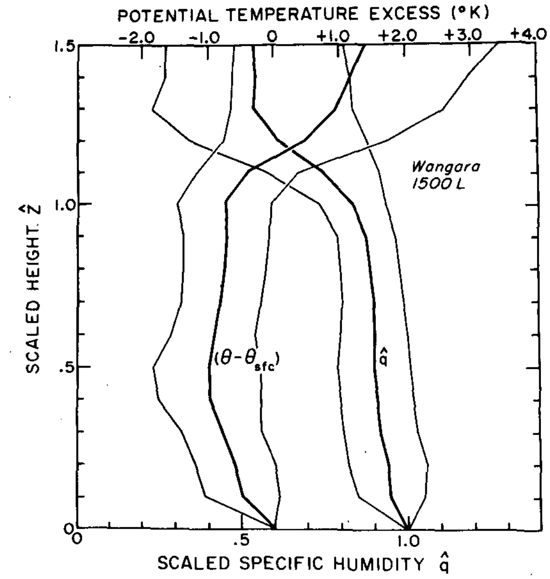

FIG. 3. Composite profiles of potential temperature and specific humidity at 1500 local standard for the 9 days during the Wangara experiment (Clarke *et al.*, 1971) on which mixing depth for virtual potential temperature is defined (Melgarejo and Deardorff 1974). Average mixed layer depth is 915 m with standard deviation of 175 m. Average surface mixing ratio is 4.1 g kg^{-1}.

necessary to distinguish between potential temperature and virtual potential temperature.

For contrast, we also analyze data from the Wangara experiment (Clarke *et al.*, 1971) for days on which mixed layers develop and low-level clouds are absent. The Wangara boundary layer is offered as a typical example of mixed layers which are nearly always well-mixed in moisture above the surface layer. Mixed layer depths were computed from the potential temperature soundings by Melgarejo and Deardorff (1974).

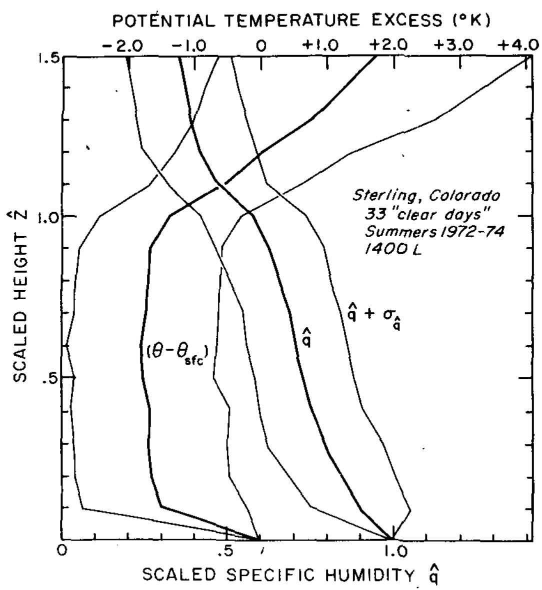

FIG. 2. Composite profiles of potential temperature and specific humidity at 1400 local standard for 33 days, 20 May–1 August, 1972–74, Sterling, Colo., on which no clouds except high thin scattered occur between 0900 and 1400 (clear days). Thin lines indicate standard deviations. Before averaging, specific humidity profiles are scaled with respect to the surface value and height with respect to the mixed layer depth, while the potential temperature values are reduced by the surface value. The average mixed layer depth is 1710 m with a standard deviation of 765 m. The average surface mixing ratio is 9.3 g kg^{-1}.

3. Influences of moisture structure

We generally expect the specific humidity gradient to decrease with height in the surface layer in the same manner as the potential temperature gradient (e.g., Dyer 1967) and thus be quite small above the surface layer (Schaefer, 1976). Webb (1970) found that in the heated surface layer over Kerang, Australia, the moisture gradient decreased more slowly with height than the potential temperature gradient, but suggested that such behavior is likely due to yet undetermined observational errors. Petterssen *et al.* (1945), Malkus (1958) and Betts (1976) have noted that vertical gradients of moisture in the boundary layer complicate determination of the lifted condensation level.

Over the high plains of the United States, the significant vertical gradient of moisture may extend throughout the mixed layer. Figs. 4 and 5 show that on the average for all days at Sterling (whether cloudy or clear) in the summer of 1973 the afternoon average lower troposphere is well-mixed in terms of potential temperature, but shows little evidence of being well-mixed in terms of specific humidity. Average profiles at the four other NHRE stations also exhibit these features. While simple dimensional profiles have the advantage of independence from estimates of scaling depths, they are difficult to interpret since the height of the mixed layer depth varies from day to day. The moisture gradient is more clearly depicted in the scaled, composite profile for Sterling on clear days (Fig. 2). Note that while the moisture gradient decreases substantially above the surface layer, it still remains almost as large as the free-flow value. As will be shown, the mixed layer moisture gradient nearly vanishes on some types of clear days and is even stronger than indicated in the composite profile on other types of clear days. Note the contrast between the Sterling moisture profile and the more expected composite profile observed at Wangara (Fig. 3) where even the composite moisture gradient nearly vanishes above the surface layer.

Near the top of the NHRE mixed layer (Fig. 2) the specific humidity gradient begins to increase, reaching a marked maximum in the inversion layer capping the mixed layer. Since the profiles in the inversion layer are unavoidably smeared somewhat in the compositing process, it is difficult to assess how much of the specific humidity gradient immediately below the inversion is real. However, in the more usual case where moisture is well-mixed, Melgarejo and Deardorff (1974) and Schaefer (1976) find it useful to distinguish between the mixed layer depths for moisture and potential temperature (see Fig. 3).

Radiosonde errors in the measurement of moisture (Morrissey and Brousaides, 1970) cannot explain the large, vertical variation of moisture nor the day-to-day changes in this gradient. The composite moisture gradient is subject only to errors which are both height-dependent and nonrandom. At least two processes seem to be likely candidates for explaining the frequent occurrence of the specific humidity gradient in the NHRE mixed layer. First, the rapid entrainment of dry air associated with rapid growth into the overlying very dry free flow may act to create a moisture gradient which can never be completely destroyed by mixing. Second, the vertical moisture gradient may be forced by vertical variations of horizontal advection of moisture.

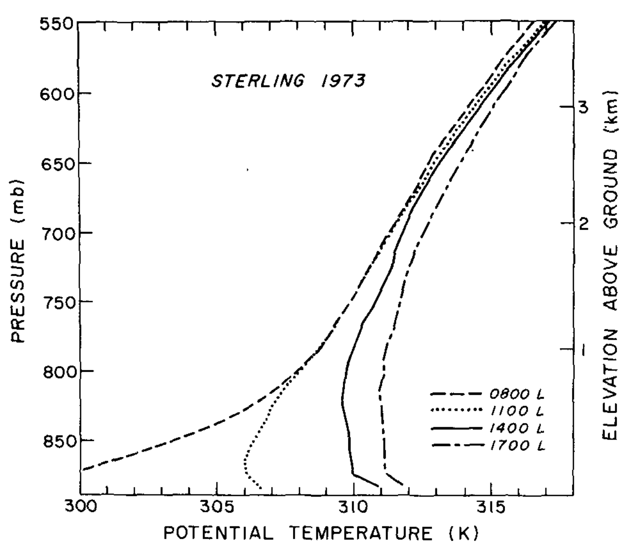

FIG. 4. Diurnal evolution of average dimensional profiles of potential temperature at Sterling, Colo., summer 1973.

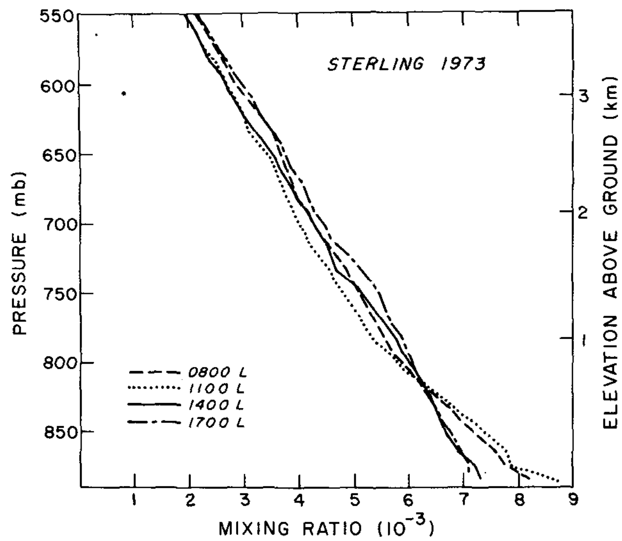

FIG. 5. As in Fig. 4 except for specific humidity.

a. Entrainment effects

The entrainment of dry air at the top of the mixed layer and surface evaporation cooperatively act to create a vertical gradient of moisture. However, this gradient will not be realized if the mixing is "sufficiently" rapid. The time scale describing the mixing of a passive scalar in a convectively mixed boundary layer is thought to be roughly $O(h/w^*)$ (Deardorff and Willis, 1974). Here $w^*=[(gh/\theta_0)(\overline{w'\theta'})_0]^{\frac{1}{3}}$ is the convective velocity scale, $(\overline{w'\theta'})_0$ is the surface virtual heat flux, h the mixed layer depth, g the acceleration of gravity and θ_0 a potential temperature scale. The "entrained dry eddies" near the top of the mixed layer are positively buoyant and may be diffused downward by small-scale turbulence or relatively weak interplume subsidence. The time scale for such mixing is probably slower than that of the buoyant plume motions. Such an explanation is consistent with the fact that strong surface evaporation does not seem to be able to maintain a moisture gradient above the surface layer and at the same time allows for the possibility that downward flux of dry air at the top of the mixed layer may be able to maintain a moisture gradient across the mixed layer. Unable to describe such effects further, we proceed by considering the mixing time scale to be $O(h/w^*)$. Then for vanishing synoptic-scale vertical motions, the depth of the fluid added to the mixed layer during the mixing time scale h/w^* is $(h/w^*)(\partial h/\partial t)$. If this depth is significant compared to the mixed layer depth, that is, if the mixed layer growth rate is comparable to the convective velocity scale, and if the free flow is substantially dryer than the boundary layer, then a significant moisture gradient in the mixed layer may be maintained. Based on laboratory measurements and aircraft data from Telford and Warner (1964) and Lenschow (1970), Deardorff and Willis (1974) estimate the entrainment rate $(\partial h/\partial t)-w_h$ to average about 2% of the convective velocity scale, where w_h is the synoptic-scale vertical motion. Noting that the high plains mixed layer growth rate averages about 0.1 m s^{-1} between 0800 and 1400, and considering w^* to be 2 m s^{-1} the ratio $(\partial h/\partial t)/w^*$ is still only approximately 5%. This calculation indicates that entrainment can explain significant vertical gradients of moisture only when the growth rate is unusually large.

Boundary layer growth and downward entrainment of dry air will be particularly rapid when the stratification of the overlying free flow is weak or nearly zero. Such flow situations may result when 1) the late morning mixed layer is engulfing remnants of a mixed layer from the previous day, 2) destabilized air from a mixed layer which developed over higher surface elevation moves over a growing mixed layer, or 3) free-flow stratification is reduced through differential horizontal temperature advection. The second condition may frequently occur east of the Rockies with westerly flow. To further assess the role of stratification, we estimate the mixed layer moisture gradient for each day from a linear regression model fitting the first five radiosonde contact points below the mixed layer top, and estimate the free-flow stratification using the first five contact points above the mixed layer top. The linear correlation coefficient r between these two variables for clear days is 0.57 (the null hypothesis that $r=0$ can be rejected at the 1% level). Of course, such a coefficient is merely an estimate of statistical relationship and does not imply a cause-effect relationship.

Unfortunately, the depth of a mixed layer growing into a nearly neutrally stratified layer cannot always be unambiguously determined from observations. In particular, the potential temperature inversion separating the two neutrally stratified layers may be undeterminably small as is predicted by simple models of inversion dynamics (Tennekes, 1973). The mass exchange between the two such mixed layers may be primarily limited to only occasional exceptionally vigorous penetrative convection from below. The limited mass exchange allows for a substantial moisture gradient across the two layers. However, observations of such cases within the limit of normal errors may be inadvertantly interpreted as one deep mixed layer with a significant moisture gradient.

b. Differential advection

Differential moisture advection within the mixed layer is likely important on days with large wind directional shear across the mixed layer. Fig. 1 indicates a significant east-west gradient of low-level moisture in the NHRE region as well as a smaller

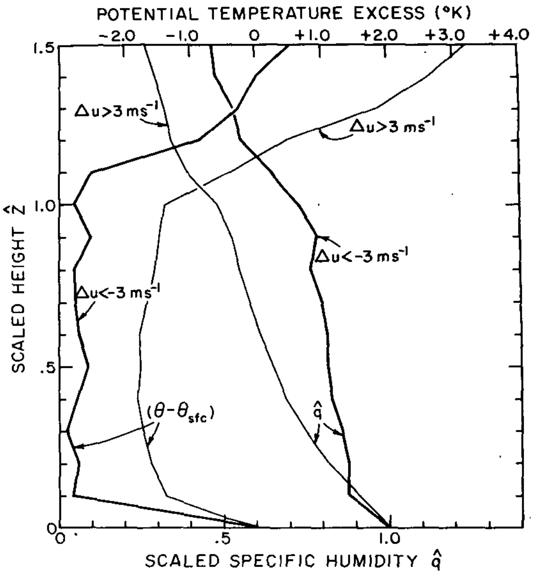

FIG. 6. Composite profiles of specific humidity and potential temperature for Sterling, 1972–74, for days on which (i) the east-west shear across the mixed layer is greater than 3 m s^{-1} as computed from the average east-west component of the first three reporting levels above the ground and the average of the first three levels below the mixed layer top (8 cases), and (ii) this shear is less than −3 m s^{-1} (3 cases). See Fig. 2 for further explanation.

north-south gradient. The concentration of a mean surface moisture gradient over the high plains east of the Rockies is also evident in the analyses of Dodd (1965). If we assume the low-level flow to be partially terrain following, then on days when the westerly flow component increases with height (or when the flow direction switches from easterly to westerly with height), we expect dry air advection to also generally increase with height, and so forth. However, analyses of horizontal structure on individual days indicates that not only does the moisture gradient field vary substantially from day to day but even the sign of horizontal advections depends on the time and horizontal length scales over which the gradients are evaluated. Nonetheless, Fig. 6 reveals that the vertical gradient of moisture in the mixed layer is indeed substantially greater on days with strong positive shear of the east-west flow component as compared to days when such shear is large negative. Of course, the above apparent correlation could be fortuitous since the shear is not only difficult to estimate from observations, but is also correlated with the east-west flow speed near the mixed layer top ($r^2=0.58$ significant at the 1% level). Therefore, from radiosonde observations alone, it may be difficult to distinguish between effects due to direct differential moisture advection, effects due to enhanced mixing or entrainment associated with advection of temperature and mixed layer depth, and difficulties in distinguishing between two separate nearly unstratified layers.

4. Conclusions and further discussion

With westerly flow over the high plains substantial vertical gradients of specific humidity throughout the mixed layer may survive convective mixing. This gradient appears to be, in part, related to differential advection of moisture as well as possible associated rapid growth of the mixed layer into very dry air aloft.

The existence of such a moisture gradient in the mixed layer can significantly influence the initiation of moist convection since the lifted condensation level is sensitive to small changes in moisture. A parcel or weakly developed updraft originating from near the surface, which likely suffers substantial entrainment as it rises through the deep vigorous convectively mixed layer, will upon reaching the mixed layer top be characterized by significantly lower moisture content than predicted by surface moisture values alone. Under such conditions, the elevation (above ground) of the updraft origin and the ability of the updraft to protect itself against entrainment (strong vertical motion, large diameter) become particularly important. Such possibilities complicate estimation of parcel stability from surface measurements.

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