Distributions of Surface-Layer Buoyancy Versus Lifting Condensation Level over a Heterogeneous Land Surface

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ABSTRACT

Onset and coverage of small cumulus clouds depend on the relative abundance of surface-layer air parcels possessing favorable buoyancy and moisture—two variables that are coupled through the surface energy budget. This abundance is described using a joint frequency distribution (JFD) as a function of virtual potential temperature θ , and height of the lifting condensation level z_{LCL} . It is shown analytically that the shape and spread of this JFD depends on the ranges of Bowen ratios and solar forcings (albedoes, cloud shading, etc.) that exist within a domain of heterogeneous land use.

To sample the character of such JFDs in the real atmosphere, a case study is presented using turbulence data gathered by aircraft flying in the surface layer of southwest France. This case study includes 4 days of clear skies during the Hydrologic Atmospheric Pilot Experiment (HAPEX) of 1986. The full flight track during HAPEX overflew a wide range of land use including evergreen forest, corn, vineyards, pastures, and irrigated fields over varied topography. The JFDs from these full tracks are found to be quite complex, being frequently multimodal with a convoluted perimeter. However, when a full track is broken into segments, each over a subdomain of quasi-homogeneous land use, the resulting segment JFDs are mono-modal with simpler topology.

Such a characterization of JFDs provides guidance toward eventual subgrid cumulus parameterization in large-scale forecast models, with associated impacts in aviation forecasting, pollutant venting and chemical reactions, vertical dispersion and turbulence modulation, and radiation balance in climate-change models.

1. Surface heterogeneity and cumulus cloud ensembles

To an observer on the ground, fair-weather, nonprecipitating, boundary-layer cumulus clouds (BLCu) often appear to have uniform cloud-base heights. However, aircraft and lidar measurements indicate a range of base heights from cloud to cloud, even within a relatively small (order of 20 km) horizontal domain at an instant in time (Stull 1984; Stull and Eloranta 1985; Crum and Stull 1987). The variation of cloud-base heights is directly related to the distribution of lifting condensation levels (LCLs) in the surface layer, which in turn is modulated by characteristics of the underlying heterogeneous surface (Rabin et al. 1990).

The strong relationship between BLCu and the surface can be explained by observations (Crum et al. 1987) of large-diameter cores of thermals, in which surface-layer air can rise undiluted to the top of the mixed layer. Because these thermal cores contain the moistest and most buoyant air, they are the structures most likely to form clouds. Actual base height for any cloud should equal the theoretical LCL of surface-layer air, as was indeed verified by Stull and Eloranta (1985) for the 1983 Boundary Layer Experiment (BLX83, Stull and Eloranta 1984).

Variations in cloud depth (Lopez 1977) and spacing (Joseph and Cahalan 1990) are also observed in a BLCu ensemble. Cloud-top height is determined in part by the buoyancy of air rising from the surface layer, relative to the ambient sounding. One can use virtual potential temperature θ , as an appropriate measure of buoyancy. Large-diameter thermal cores serve as a conduit to carry air with unmodified θ , from the surface layer up to the LCL, above which θ increases because of latent heating within the cloud. Thus, the cloud-top height distribution is also controlled by temperature

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FIG. 1. Over heterogeneous ground (indicated by different shadings of the baseline), air parcels in the surface layer acquire different virtual potential temperatures (sketched as circles of different shadings, and indexed by i). Warmer parcels are more buoyant relative to the environmental sounding (dashed line at left) and rise higher (as indicated by the length of the vertical arrows). Each air parcel has a lifting condensation level (indicated with a white bar). Only those parcels buoyant enough to rise above their LCLs can make clouds (shaded).

and moisture distributions in the surface layer, which are modulated by characteristics of the underlying heterogeneous surface.

From the previous arguments, one can hypothesize that a statistical description of surface-layer air can be used to diagnose the size and morphological distributions of a BLCu ensemble. This is our approach. As sketched in Fig. 1, any one thermal has an LCL and an associated buoyancy, both of which affect the cumulus-forming potential of that one thermal. The frequency of occurrence of thermals as a function of their LCL and θ_0 is thus needed to describe the cumulus potential (CuP) of an ensemble of thermals. Although bivariate frequency distributions have been used for other characteristics of boundary-layer thermals (Mahrt and Paumier 1984; Deardorff and Willis 1985; Wyngaard and Moeng 1992) and photon transmission through cloud fields (Davis 1990), the joint distribution of LCL and θ_0 has not yet been investigated.

Wilde et al. (1985) did some preliminary research in this area. They used case-study data gathered by the National Center for Atmospheric Research (NCAR) Queen Air aircraft flying in the surface layer during BLX83 to measure the 1D frequency distribution of LCL heights. They found that a double-exponential distribution model fit the LCL data quite well. Alternative distribution models for LCL or relative humidity, such as a Gaussian model for cloud coverage, have been suggested by Ek and Mahrt (1991).

Wilde et al. used ground-based lidar data to directly measure the heights of thermal tops and cloud tops.

Thermal-top measurements are directly related to the distribution of air in the entrainment zone (Crum and Stull 1987), as defined by Deardorff et al. (1980). Because Wilde et al. found it impossible to combine the lidar-measured heights with the aircraft-measured LCLs to form joint frequency distributions (JFDs), they were forced to estimate BLCu onset and coverage from the convolution of two independent univariate distributions for LCLs and thermal tops. Although their cloud forecasts were reasonable, one might expect that better forecasts could be possible if the dependencies between LCLs and thermal buoyancy could be included in the form of a JFD.

Wetzel (1990) tested the approach of Wilde et al. and suggested that a more practical BLCu coverage model might be possible if temperature could be used to estimate the potential rise of thermals, instead of using expensive lidar-measured thermal tops. We support such a notion and investigate here the relationship between surface-layer temperature and LCL.

The primary goal of our research is to use case-study field-experiment measurements to develop a preliminary picture of such JFDs of surface-layer air and to predict the likely mechanisms by which heterogeneous surfaces modulate those distributions. Siebert et al. (1992) demonstrated the importance of land surface characteristics on the energy state of the surface layer. The need for large-scale models to maintain the proportional area of each subgrid land surface type to accurately represent sensible and latent heat flux in heterogeneous terrain was recognized by Blyth and Dolman (1993).

The approach of using the distribution of surface-layer LCLs or humidities to forecast partial cloudiness requires more boundary-layer information than schemes that use a single mean humidity to parameterize subgrid cloud coverage (Walcek 1994). These latter methods generally ignore the formative and dissipative processes involved in boundary-layer cumulus (Xu and Krueger 1991) and can also be sensitive to the horizontal resolution of the model (Kristjánsson 1991). One shortcoming of surface-layer distribution methods is their neglect of cloud-top processes such as entrainment and radiation. Telford and Chai (1993) and Telford et al. (1993) found that entrainment of air from cumulus that had previously formed and dissipated had an effect on the subsequent development and radiative properties of clouds that formed later in the same region. The effects of cloud-top radiation and entrainment are becoming much better understood as research on marine stratocumulus clouds is advancing (Bechtold et al. 1991; Bechtold and Pinty 1993; Betts 1993; Bretherton 1993; Kvanstø 1991; Moeng 1993; Paluch and Lenschow 1991; Siems and Bretherton 1992; Wang 1993; and Wang et al. 1993). Such cloud-top processes are not addressed here.

Fair weather cumulus formed from surface-layer air can impact climate both via transport of greenhouse gases and by altering the radiation budget (Arking

1991; Stull 1992). These clouds also impact turbulence intensity, pollutant dispersion, venting of pollutants, aqueous-phase chemical reactions of pollutants, and aircraft operations. While cumulus ensemble diagnoses and forecasts are the ultimate motivations for this research, the present research takes a necessary first step—namely, the observation and statistical characterization of surface-layer air over one sample heterogeneous surface.

The surface energy budget is used in section 2 to develop a theory for the coupling between LCL and θ_v . In section 3, we briefly review the Hydrologic Atmospheric Pilot Experiment (HAPEX), from which we acquired temperature and moisture case-study data in the surface layer over a heterogeneous surface. In this section, we identify subdomains of nearly uniform land use within the larger HAPEX domain and discuss data calibration and analysis procedures. Resulting measured JFDs over each subdomain are presented in section 4, and the nature of these distributions is discussed. In section 5 the statistical characteristics of the observed JFDs are estimated.

2. Coupled horizontal variations of moisture and temperature in the surface layer

We focus on free convection over land, in conditions of light to moderate wind. Hechtel et al. (1990) and Hadfield et al. (1988) found that whenever the winds are faster than about 1 or 2 m s⁻¹ during free convection, the atmospheric influence of individual farm fields and land-use elements are naturally aggregated and blended by the wind within the lower surface layer. At altitudes of 100 m above ground, where the King Air aircraft flew, *individual turbulent fluctuations* cannot usually be identified with individual surface features. However, for horizontal scales (>5 km) significantly larger than the mixed-layer depth, mesoscale variations in land use can cause observable mesoscale variations in *turbulence statistics*. For these mesoscales, we hypothesize that the statistical nature of turbulent fluctuations of LCL and θ_v as measured about 100 m above ground can be identified with mesoscale regions of relatively uniform land use.

A theoretical relationship between temperature and moisture heterogeneities in surface-layer air is developed here. From the resulting theory we identify key parameters controlling the JFDs for surface-layer air. These parameters help to organize the data and statistical analyses in sections 4 and 5.

Define $\bar{\theta}_{ML}$ and $\bar{r}_{ML}$ as the horizontally averaged potential temperature and water-vapor mixing ratio at altitudes near the middle of the convective mixed layer (ML), at some instant in time. For a scenario of daytime solar heating of the surface, air in the surface layer (SL) must be warmer and moister than in the ML to cause heat and moisture fluxes away from the surface.

The amounts of these excesses depend, in part, on the nature of the underlying surface, and thus can vary spatially (x) in the surface layer over a horizontally heterogeneous landscape. Define these temperature and mixing-ratio excesses as $\theta'(x) \equiv \theta_{SL}(x) - \bar{\theta}_{ML}$ and $r'(x) \equiv r_{SL}(x) - \bar{r}_{ML}$, respectively. To simplify the notation, we will write simply θ' and r' for these excesses.

In the present context, these primed values include only the influence of surface processes. Other processes, such as entrainment, are lumped into $\bar{\theta}_{ML}$ and $\bar{r}_{ML}$. We will assume a quasi-steady surface layer where the intensity of turbulence and the shapes of the temperature and mixing ratio profiles are maintained, even while the average temperature and humidity of the whole mixed layer are changing.

a. Surface energy balance

For nonadvective, quasi-steady conditions over land during daytime, the net imposed surface heat flux Q_F is partitioned into sensible Q_H and latent Q_E heat fluxes into the air, according to the surface energy balance

$$Q_F = Q_H + Q_E. \quad (1a)$$

The imposed flux includes downwelling solar radiation K_d modulated by shading by clouds of coverage σ , attenuated by clear sky absorption described as a transmissivity τ , reduced by reflection from the surface of albedo α , and corrected for multiple reflections with factor μ . It also includes longwave fluxes L_* , and is reduced by conduction of heat into the ground Q_G :

$$Q_F \approx \mu K_d \tau (1 - \sigma)(1 - \alpha) + L_* - Q_G. \quad (1b)$$

Sensible heat flux is driven by a temperature excess in the surface layer:

$$Q_H = \rho C_p w_T \theta',$$

where ρ is air density, C_p is the specific heat of air, and w_T is a transport velocity (Stull 1988). The transport velocity can be interpreted as conventional surface drag ($C_D M$), where M is wind speed and C_D is drag coefficient, or as a convective transport ($C_* w_*$), where w_* is the Deardorff convective velocity and C_* is a convective drag coefficient (Stull 1994). In this study, we will focus on the free convection interpretation. A similar expression for latent heat flux is

$$Q_E = \rho L_v w_T r',$$

where L_v is the latent heat of vaporization of water.

Define a “forcing temperature” θ_F for heat input by

$$Q_F \equiv \rho C_p w_T \theta_F,$$

which is equivalent to the temperature excess of surface-layer air in the absence of evaporation. From (1b) we see that θ_F increases with greater solar input (e.g., sun higher in the sky), darker surfaces, and fewer clouds.

With these definitions, the surface energy balance (1a) becomes

$$\theta_F = \theta' + r'/\gamma, \quad (2)$$

where the psychrometric constant is $\gamma = C_p/L_v = 0.4$ (g/kg)·K⁻¹. A physical interpretation of (2) is that the heating imposed at the surface causes temperature and humidity excesses within the surface layer. Even if θ_F were horizontally uniform, any variations of θ' must be compensated by opposite changes of r' to maintain the energy balance.

b. Bowen ratio and air parcel state

The Bowen ratio ($B = Q_H/Q_E$) is controlled by the amount of moisture available for evaporation and transpiration at the surface (Oke 1987) and thus acts as an additional constraint imposed on the surface layer. Using the expressions for sensible and latent heat above, the Bowen ratio can be rewritten as

$$B = \theta' \gamma / r'. \quad (3)$$

Equations (2) and (3) are easily solved for the temperature and mixing ratio excesses that occur in surface-layer air parcels:

$$\theta' = \frac{B\theta_F}{1+B} \quad (4)$$

and

$$r' = \frac{\gamma\theta_F}{1+B}. \quad (5)$$

It comes as no surprise that an increase of heat input θ_F can increase both r' and θ' , while an increase in surface moisture as measured by the inverse of the Bowen ratio can increase r' at the expense of θ' .

As suggested by Fig. 1, joint distributions of θ_v and LCL can be used more directly than distributions of θ' and r' to diagnose BLCu cloud cover. Using (4) and (5) as starting points, we derive equations for LCL and θ_v as a function of imposed forcings θ_F and B .

c. LCL height

The height z of the LCL above any measurement height is quite well approximated (Barnes 1968; Wilde et al. 1985) by

$$z \approx a(T - T_d), \quad (6)$$

where constant $a = 125$ m K⁻¹ in the mixed layer, T is air-parcel temperature, and T_d is dewpoint temperature. By expanding $T \equiv T_{ML} + T'$, $T_d \equiv T_{dML} + T'_d$, where $T_{dML} \equiv T_d(r_{ML})$, and $z' \equiv z - z_{ML}$, where $z_{ML} \approx a(T_{ML} - T_{dML})$, the LCL height change equation becomes

$$z' \approx a(T' - T'_d).$$

The air-parcel dewpoint temperature T_d is related to mixing ratio r by an approximation to the Clausius–Clapyron equation

$$\frac{dr}{dT_d} \approx \frac{c_r r}{T_d^2},$$

where $c_r \equiv L_v/R_v = 5423$ K is the ratio of latent heat of vaporization to water-vapor gas law constant. This expression is approximate because latent heats are not quite constant with temperature and pressure and because the vapor pressures that appear in the Clausius–Clapyron equation have been approximated by $e^{-1}de \approx r^{-1}dr$.

Use a reference state corresponding to the mixed-layer (ML) conditions and approximate the derivatives as deviations from this state: $dr/r \approx r'/r_{ML}$ and $dT_d/T_d^2 \approx T'_d/T_{dML}^2$. Thus, the Clausius–Clapeyron equation can be rearranged to be

$$T'_d \approx (r'/r_{ML})(T_{dML}^2/c_r).$$

This expression for dewpoint change can be used in the expression for LCL height change to give

$$z' \approx a \left[T' - \left(\frac{r'}{r_{ML}} \right) \left(\frac{T_{dML}^2}{c_r} \right) \right]. \quad (7)$$

Finally, substituting (4) and (5) into (7) and using $T' = \theta'$, we get the desired expression for LCL height change as a function of external forcing parameters θ_F and B :

$$z' \approx \left[\frac{a\theta_F}{1+B} \right] \left\{ B - \left(\frac{\gamma}{r_{ML}} \right) \left(\frac{T_{dML}^2}{c_r} \right) \right\}. \quad (8a)$$

To simplify the notation, define $B_{ML} \equiv (\gamma/r_{ML}) \times (T_{dML}^2/c_r)$. Then (8a) can be rewritten as

$$z' \approx \left[\frac{a\theta_F}{1+B} \right] \{ B - B_{ML} \}. \quad (8b)$$

The factor in curly brackets in (8) causes a sign change of z' , depending of the magnitude of B relative to B_{ML} . The last term in the curly brackets is a function of only the ML conditions, is of order unity, and varies with humidity as plotted in Fig. A1 in the appendix. For example, $B_{ML} = 0.741$ for $r_{ML} = 0.008$ g/g and $T_{dML} = 10.5^\circ\text{C}$ at $P = 100$ kPa. For values of B larger than B_{ML} (i.e., relatively dry surfaces), (8b) shows that the LCL of the surface-layer air parcel increases with solar forcing θ_F . Namely, greater solar input, fewer clouds, darker surfaces, or any other process that causes larger θ_F will create a drier air parcel ($r' < 0$), which must rise higher before it can form a cloud than parcels of the reference state (r_{ML}). Conversely, for smaller values of B corresponding to a relatively moist surface, increases in solar forcing θ_F cause lower LCL heights.

d. Virtual potential temperature, θ_v

Starting with the definition of virtual potential temperature for unsaturated air

FIG. 2. Example of virtual potential temperatures θ_v and LCL heights z_{LCL} as a function of Bowen ratio B (dashed lines) and thermal forcing temperature θ_F (solid heavy lines). Larger Bowen ratios occur over drier ground. Stronger thermal forcings occur with higher sun angles, darker surfaces, and less cloud shading.

$$\theta_v = \theta[1 + 0.61r], \quad (9)$$

expand $\theta_v = \theta_{vML} + \theta'_v$ and similarly expand θ and r . Define $\theta_{vML} \equiv \theta_{ML}[1 + 0.61r_{ML}]$. Then one finds

$$\theta'_v = \theta' + 0.61(\theta_{ML}r' + \theta'r_{ML} + \theta'r'). \quad (10)$$

Substituting (4) and (5) into (10) yields the excess parcel buoyancy as a function of external forcings:

$$\theta'_v = \frac{B\theta_F}{1+B} \left\{ 1 + 0.61 \left[\frac{\theta_{ML}\gamma}{B} + r_{ML} + \frac{\gamma\theta_F}{1+B} \right] \right\}. \quad (11a)$$

A scale analysis suggests that the second term in square brackets is an order of magnitude smaller than the first, and the last term in square brackets is two orders of magnitude smaller. Thus, to good approximation

$$\theta'_v \approx \frac{B\theta_F}{1+B} \left\{ 1 + \frac{\theta_{ML}\beta}{B} \right\}, \quad (11b)$$

where $\beta \equiv 0.61\gamma \equiv (1 - \epsilon)(\gamma/\epsilon) = 2.44 \times 10^{-4} \text{ K}^{-1}$. Physically, (11) shows that excess parcel buoyancy above the reference state can be caused by increased solar input, reduced cloud cover, darker surfaces, and drier surfaces.

e. Theoretical behavior of joint distribution of LCL versus θ_v

By using both (8) and (11), we can anticipate the characteristics of joint frequency distributions of LCL versus θ_v in the surface layer. For example, suppose the

reference state is given by $P = 100 \text{ kPa}$, $\theta_{ML} = 290 \text{ K}$, and $z_{ML} \text{ (LCL)} = 800 \text{ m}$. Solving (8) and (11) for a variety of values of forcings B and θ_F , and adding the resulting excess values to the reference state, yields the modified state of surface-layer air parcels that is plotted in Fig. 2.

Straight lines of constant Bowen ratio B fan out with different slopes radially from the reference state, as shown in Fig. 2. Diagonal parallel lines of constant forcing temperature θ_F run from lower left to upper right. The slopes of the radial lines of constant Bowen ratio are simply z'/θ'_v , which can be found by combining (11) into (8) to eliminate θ_F :

$$z' = a\theta'_v \frac{(1 - B_{ML}/B)}{(1 + \theta_{ML}\beta/B)}. \quad (12a)$$

But $\theta_{ML}\beta$ is of order 0.075, which leads to a simpler approximation

$$z' \approx \theta'_v a[1 - B_{ML}/B]. \quad (12b)$$

To find the equations for the diagonal parallel lines, combine (11) and (8) to eliminate B :

$$z'(1 - \theta_{ML}\beta) = \theta'_v a(1 + B_{ML}) - a\theta_F(\theta_{ML}\beta + B_{ML}), \quad (13a)$$

which can also be approximated by

$$z' \approx \theta'_v a(1 + B_{ML}) - a\theta_F B_{ML}. \quad (13b)$$

The slopes of the B and θ_F lines provide a framework within which the nature of the JFDs can be explained and modeled.

f. Discussion and physical interpretation

One can measure the LCL and θ_v for each air parcel in the surface layer, such as along an aircraft flight track (Fig. 3), and plot these air-parcel states as data points in Fig. 2. For a set of many air parcels, the density of points in Fig. 2 gives the frequency of occurrence, which can be contoured (e.g., Fig. 4a). Different surface characteristics are likely to

FIG. 3. As an aircraft (triangular symbol) flies in the surface layer, measurements along the horizontal flight leg can be considered as air parcels (circles). Although those parcels are not really independent (e.g., neighboring parcels in a thermal indicate similar characteristics of the thermal) the relative number of parcels having a specified characteristic provides a reasonable sample statistic for a corresponding fraction of surface-layer air. The average height of the mixed layer is z_{ML} .

FIG. 4. Shaded contours represent relative frequency of occurrence of surface-layer air parcels having various idealized z_{LCL} and θ_v characteristics. (a) Natural variability over a horizontally uniform surface. (b) Solar forcing variations caused by scattered cloud shading or surface albedo heterogeneities over a dry surface. (c) Same as (b) but over a wetter surface. (d) Land wetness variations due to irrigation or plant transpiration variations. (e) Complex joint frequency distribution (JFD) over a large heterogeneous region. (f) Mono-modal JFD over a subdomain of (e) having nearly uniform surface characteristics.

cause different shapes of the JFD contours, as described below.

For a homogenous surface, if there were no random turbulence fluctuations, then all the surface-layer data would ideally fall on a single point in Fig. 2. A more likely scenario over a homogenous surface would allow

a small spread of surface-layer data due to natural variability, where these points would likely be clustered with strong central tendency about the ideal point (Fig. 4a).

Heterogeneous solar forcings would cause a spread of data points along a line of constant Bowen ratio (Figs. 4b,c). Such heterogeneity could be caused by

TABLE 1. Cloud-free flight conditions during HAPEX. All times are local European "summer" time (LT = UTC + 2 h).

Date 1986	Flight number	Flight segment	Starting time (LT)	Ending time (LT)	Weather (from flight logs)
9 June	13	T1, S1-5	11:40:04	11:51:24	Generally clear skies in a large area of subsidence. Winds from 110° at 5 m s ⁻¹ throughout the BL. No cumulus or stratus, but some light cirrus.
		T1, S6-8	11:52:15	12:00:00	
		T1, S9-12	12:00:15	12:15:30	
		T2, S12-9	13:27:28	13:40:00	
		T2, S8-6	13:40:15	13:51:56	
		T2, S5-1	13:53:40	14:02:53	
		T3, S1-5	14:10:03	14:21:28	
		T3, S6-8	14:22:20	14:34:00	
16 June	15	T3, S9-12	14:35:00	14:45:47	Clear. Observed wind gradient with almost calm wind in south, to ESE wind to the north.
		T1, S1-5	11:45:10	11:56:40	
		T1, S6-8	11:57:20	12:08:25	
		T1, S9-12	12:09:00	12:22:20	
		T2, S8-6	13:55:10	14:06:55	
		T2, S5-1	14:07:30	14:17:35	
		T3, S1-5	14:27:10	14:38:40	
		T3, S6-8	14:38:44	14:50:50	
19 June	16	T3, S9-12	14:52:00	15:01:55	Clear skies and nearly calm wind. Shallow BL for most of day (750 m), but grew rapidly at the end of the flight (2000 m). Thunderstorms visible over the Pyrenees all afternoon.
		T1, S1-5	14:52:15	15:02:30	
		T1, S6	15:03:25	15:07:30	
		T1, S7-8	15:09:01	15:15:21	
		T1, S9-12	15:15:52	15:27:03	
		T2, S12-9	15:29:20	15:40:31	
		T2, S8-6	15:40:50	15:52:45	
		T3, S1-5	16:05:36	16:16:02	
2 July	21	T1, S1-5	11:38:57	11:50:00	A ridge of high pressure caused fair weather. Light winds from the NE in the BL with no low level clouds. A patch of cirrus drifted over the area from the SW. Very hazy in the BL.
		T1, S6-8	11:50:34	12:02:30	
		T1, S9-12	12:03:00	12:14:03	
		T2, S12-9	13:34:26	13:46:48	
		T2, S8-6	14:14:21	14:30:02	
		T2, S5-1	14:36:18	14:46:15	
		T3, S1-5	15:01:11	15:11:44	
		T3, S6-8	15:12:35	15:25:02	

- albedo variations associated with agricultural practices such as crop type, crop maturity, and irrigation

- paved versus unpaved regions in urban and sub-urban areas
- partial shading of the homogeneous ground by scattered or broken clouds.

Bowen ratio variations would cause the data points in the surface layer to spread along a line of constant solar forcing (Fig. 4d). These Bowen ratio variations could be caused by

- irrigated versus nonirrigated farm fields
- paved versus vegetated landscapes
- crops experiencing varied moisture stress and transpiration rates
- slight topographic variations causing variations in the water-table depth and moisture availability.

Obviously, a more realistic scenario would include horizontal variations of everything: albedo, cloudiness, moisture, transpiration, etc. The resulting surface-layer data points over a truly heterogeneous surface could spread along both the Bowen ratio and solar forcing

axes with perhaps multiple modes (Fig. 4e). However, if we purposely focus on a subdomain that has nearly uniform surface characteristics within a mesoscale region of greater than 10 km, then the spread of data points would be somewhat constrained and nearly mono-modal (Fig. 4f) and might be capable of being quantified and parameterized.

By quantifying simple joint distributions for quasi-homogeneous mesoscale surface types (such as in Fig. 4f) and then adding them together as building blocks in amounts proportional to the relative amounts of different land-use classes (such as in Fig. 4e), it should be possible to construct joint distributions over arbitrarily complex heterogeneous surfaces. It is with this motivation that we analyze HAPEX field experiment data as a case study to discover some of the types of JFDs are possible in nature.

3. HAPEX field experiment—a case study

The Hydrologic Atmospheric Pilot Experiment (HAPEX-MOBILHY) was conducted in southwest France in 1985 and 1986 (André et al. 1986) to examine subgrid processes within a typical climate-model

FIG. 5. Location of "S" flight track during HAPEX and identification of segment numbers and key points E–F.

grid box. The 100 km $\times$ 100 km domain (Choisnel et al. 1987) between Bordeaux and Toulouse included several mesoscale regions of relatively homogeneous landscapes: flat farmland, rolling hills, flat forest areas, and their respective transition zones.

Although the entire HAPEX field experiment was conducted during a period of 2 years, the data used here are from a special observation period (SOP) from 9 May to 15 July 1986, which captured the transition from moist spring to dry summer. To achieve good temporal as well as spatial resolution in this climatic dataset, the instrumented King Air aircraft from the NCAR was flown approximately once every 3 days during the SOP. Flights were postponed only on days with heavy or continuous precipitation, fog, or other flight difficulties.

Variable surface heterogeneity can be induced by partial shading of the ground by clouds. For this initial work, however, we chose cloud-free days to examine the heterogeneity caused by the land use alone. It was a matter of chance for the aircraft to fly on a cloud-free day. All four of the available cloud-free days having the proper flight pattern were analyzed in our study (Table 1), but just a couple examples are shown in this paper to save space.

A flight pattern roughly in the shape of the letter "S" was frequently flown (see Fig. 5), taking the aircraft over the different surface types. An average altitude of 100 m above ground level was maintained during most of these flights, providing data in the upper surface layer. The aircraft flew at nearly constant speed (approximately 80 m s⁻¹) during any one horizontal flight track in the surface layer; hence, the data points rep-

resent equal lengths of air (approximately 4 m) along the flight track. Additional altitudes were also flown at 40% and 70% of the mixed layer (ML) depth; however, only the surface-layer data are used here. Finally, ascent or descent aircraft soundings from the surface to above the top of the ML or cumulus-top altitudes were occasionally flown at some of the key points.

Using maps of land use, topography, and airborne and satellite photographs, we split flight tracks into 12 shorter segments, each over a quasi-uniform landscape (Fig. 5). The surface under each segment was classified into the following five land uses: flat farmland, farmland–forest mix (transition), flat forest, steep hilly mixed agriculture, and moderate hilly mixed crop (vineyards). Nevertheless, within each mesoscale segment there was a range of individual land uses. The starting and ending latitude and longitude for each flight segment are listed in Table 2.

The following is a summary of definitions used to describe aircraft locations (see Fig. 5):

- **Flight:** The period between take-off and landing of the aircraft on any one day.
- **Key points:** E, F, G, and H are locations marking the vertices and ends of the S pattern.
- **Track:** one pass of the whole S pattern (for example: E–F–G–H).
- **Leg:** section between two consecutive key points (example: EF, FG, or GH).
- **Segment:** a portion of the flight track having approximately uniform surface characteristics of vegetation and topography. Segments are numbered 1 through 12 for identification (see Fig. 5).

Because the aircraft was flown over visual landmarks, it is known that the planned track was accurately followed within 0.2 km due to the skill of the pilots. However, the airborne inertial navigation system (INS) incurred a "drift" that was determined to be nonlinear and unpredictable and that varied from flight to flight as well as within each flight. In other words, when the

TABLE 2. Latitude and longitude at the endpoints of flight segments.

Segment index	Latitude (°N)	Longitude (°E)	Topography and land usage
Start (E)	43.6583	–0.58	
1	43.6477	–0.5212	Flat farm–forest transition
2	43.6188	–0.3198	Steep hilly mixed agriculture
3	43.6120	–0.2738	Moderate hilly mixed agriculture
4	43.5832	–0.0312	Steep hilly mixed agriculture
5 (F)	43.5783	–0.0133	Flat farmland
6	43.6627	–0.00581	Flat farmland
7	43.9546	–0.04086	Moderate hilly mixed agriculture
8 (G)	44.0667	–0.0567	Flat farm–forest transition
9	44.2904	0.01511	Flat forest
10	44.3377	0.03054	Flat farm–forest transition
11	44.4877	0.07939	Moderate hilly mixed agriculture
12 (H)	44.5333	0.0967	Flat farmland

recorded flight tracks were plotted on a map, the resulting flight tracks were offset from the actual track flown as observed by the pilots and airborne scientists. Therefore, a manual location adjustment was applied to each flight track to ensure correlation between the actual position and the data. These corrected navigation data were used when splitting the recorded aircraft data into the flight segments.

Nonstationarity is a problem because the mean boundary-layer depth and thermodynamic state usually evolve during the 30 min that it takes to fly any full flight track. Nonstationarity is quantified during our analysis procedure and is removed by adjusting the results from each different flight segment to a common time that corresponds to the midpoint of the flight track, as discussed in section 4.

The surface-layer flight legs for the cloud-free cases were further screened to eliminate portions with questionable data. Plots of aircraft pitch and roll were examined for periods when the aircraft was not straight and level, such as when making a turn or avoiding obstacles. Additionally, the flight path was examined for unscheduled detours, possibly taking the aircraft over a different surface type. Finally, data portions were discarded for time periods with instrument malfunctions. The resulting segments of useable data were generally shorter than the nominal starting and ending times that were logged by the airborne scientists (Stull 1986). Table 1 shows the flight tracks and segments used for this study.

Mean and turbulence data were sampled at a higher frequency and averaged down to 20 Hz. Instrumentation and preprocessing of the raw data by NCAR are described by Hildebrand (1988). Fast-response temperature measurements were obtained from two fast-response thermometers, part of the standard turbulence instrumentation provided by NCAR. Ambient static pressure was measured from the static pressure port on the aircraft.

A Lyman-alpha hygrometer was used to obtain high-frequency moisture data. Pre- and postflight calibration was done by inserting known reference gases in the detection path (Eloranta et al. 1989), and segment-to-segment drift was removed by calibrating against the airborne dewpoint hygrometer. Details are given in the appendix.

4. Observed joint frequency distributions

a. Method

Because θ_v of a parcel is conserved during unsaturated adiabatic ascent, this quantity can be calculated from surface-layer data. The mixing ratio r is computed from the absolute humidity measured by the aircraft and is used in (9) to compute θ_v .

The LCL height was determined by numerically "lifting" each surface-layer data point (parcel) dry adiabatically until the calculated saturation mixing ratio

equaled the measured mixing ratio. This method is a bit more accurate than Eq. (6). Heights were determined from the hypsometric formula, using temperatures and humidities (with 0.05-kPa vertical resolution) from the nearest slant ascent or descent sounding flown by the aircraft. An iterative procedure was used, where at each increment of height the new parcel temperature was found from the dry adiabatic lapse rate. Saturation mixing ratio was determined at each increment using Tetens' formula (Stull 1988).

The LCL height and virtual potential temperature were used to sort each of the airborne observations into bins of width $\Delta\theta_v = 0.1$ K and $\Delta z_{LCL} = 25$ m. The center of each bin is used to define the bin location. The result is a JFD of frequency of occurrence of air with various LCL and θ_v values. Separate JFDs were found for each flight segment. The average number of data points per flight segment was roughly 3000, but numbers ranged between 20 to over 8000 depending on the length of the flight segment.

To remove effects of boundary-layer nonstationarity during flight along a track, a linear interpolation scheme was used to slightly offset the LCL and θ_v location of the segment JFD, on the basis of the observed track-to-track time evolution. This method of interpolation assumed that changes are linear, which is reasonable because time intervals are relatively small (less than 30 min). The interpolation scheme was modified for those special situations where segment data were missing from a track. For this situation, the interpolation was performed with the corresponding segment of the next track, which would likely cause errors generally less than 10%, based on comparison with non-missing data.

A relative difference (θ'_v, z'_{LCL}) was then calculated between the mode of the time-corrected segment JFD and mean from the whole track. This information is used to relate segment JFD characteristics to the underlying landscape category. For example, a surface characterized by a higher-than-average Bowen ratio would likely have a higher LCL and warmer θ_v (i.e., positive θ'_v and z'_{LCL}), given the same solar insolation (see discussion in section 2). Although it is expected that variations in external forcings, such as advection and entrainment, also play a role in determining the characteristics observed, these variations will not be examined here.

We also examined the relative change in $\Delta z_{LCL}/\Delta\theta_v$ of the segment JFD mode positions to quantify the translation of the JFD for each landscape category. This quantity is independent of time and gives some indication of the forcings present. This ratio is positive (rising LCL and warming ML) when the ML is drying and warming, implying entrainment of dry air from the free atmosphere. A negative ratio suggests lowering LCL, typical when surface evaporation is strong.

b. Case study results

1) JUNE 1986—FLIGHT 13

Synoptic conditions were ideal for clear skies on this day. On the previous day, a ridge of high pressure at the surface extended from the Azores into France. On the day of the experiment there were generally clear skies and light winds in a large area of subsidence and only localized reports of cirrus (2 octas coverage). Weak southeasterly flow at the surface was influenced by the 102-kPa high situated over the Western Mediterranean. Flow at 50 kPa was variable at 5 to 7 m s^{-1} due to two strong depressions, one situated south of Iceland and the other centered over the Gulf of Cadiz (Southwest Spain). A well-defined mixed layer was observed with an inversion height of about 0.7 km (MSL $\approx$ AGL + 100 m) at the start of the flight, rising to nearly 1.4 km (MSL) at the end of the experiment (for comparison, note that *calculated* LCLs are given in m AGL.)

Some of the datasets were incomplete. The general flight pattern was consistent for each flight, and traced a path from segment 1 to 12, in order, for the first track, reversed this path (12 to 1) for the second track, and followed the original order for track 3. Although 12 flight segments of data were collected for each track, data from the last six segments of track 1 and the first five of track 3 were corrupted and therefore are not discussed here. Statistics for all valid tracks are given in Table A2 in the appendix.

An example of the joint frequency distributions (JFDs) of θ_v and z_{LCL} for the first complete track, track 2, are presented in Fig. 6. The JFDs for each segment are plotted in graphs having the same range of θ_v and z_{LCL} and can thus be easily intercompared. Evident is both the relative mean locations from segment to segment, as expected for air over different land uses, and the variety of distribution shapes. Figure 7 shows an example of the one-dimensional distributions, demonstrating the sharpness of the peak of each distribution. Note that values presented in the JFD figures here have not yet been compensated for nonstationarity.

The relative changes of each segment can be quantified with the ratio $\Delta z_{\text{LCL}}/\Delta \theta_v$. This ratio was positive for all segment JFDs on this day (see Table 3) yielding values ranging from 86.5 to $392 \text{ (m K}^{-1}\text{)}$. Additionally, $\Delta z_{\text{LCL}}/\Delta \theta_v$ values for segments 7, 8, and 9 were a factor of three or four larger than those of the other segments (Fig. 8). Although these particular segments are of differing surface type (ranging from hilly vineyards to flat forest), it is possible that their special attributes were due to a local variation in surface moisture. The calculated LCL heights remained above the mixed-layer top for the entire flight, in agreement with the observation of no boundary-layer cumulus.

Figure 9 shows the evolution of the segment 6 JFD during all three flight tracks. Tic marks indicate sorting-bin boundaries. As the mixed layer warms and dries, so does the surface-layer air in this segment of flight.

The change of the mean thermodynamic state of such segments is thus easy to predict using classical forecast equations for the mixed layer.

2) 16 JUNE 1986—FLIGHT 15

Synoptic conditions were again quite good. The surface analysis for the previous day showed a general easterly flow over the experimental region. There was some locally dense fog reported at Mont de Marsan (extreme southwest France) in the morning, but this dissipated to leave clear to partly cloudy skies later in the day. On the chosen case-study day, the weather over the region was warm and sunny, with rain developing along the Atlantic Coast in the evening, west of the HAPEX domain. A weak pressure gradient and southeasterly flow was observed at the surface over the region, with a cold front extending from Ireland south to Lisbon. A low center at 50 kPa over the Golfe du Lion continued to influence the region, resulting in ENE flow at 5 m s^{-1} . Conditions were noted to be uniform over the experimental region for flight 15, with clear skies and light and variable winds over the entire flight path. The depth of the mixed layer grew from a low of 0.9 km (MSL) to a maximum of 1.3 km at the end of the flight in the late afternoon.

Data for track 1 is complete for this case, whereas the last four segments of track 2 and the first two of track 3 were suspect and discarded. Again distributions are primarily mono-modal and contiguous, with a tendency for the mode to be skewed to the lower left of the distribution. Unadjusted values of θ_v ranged from 296.6 to 299.8 K , while z_{LCL} ranged from 960 to 1420 m AGL . The majority of the distributions tend to be oriented along a vertical or horizontal axis, with the exception of segment 9, which seems to prefer the diagonal in this case.

Segments evolved consistently with each other for this flight. Each exhibited a positive $\Delta z_{\text{LCL}}/\Delta \theta_v$, which increased with time (Fig. 8), indicating a warming and drying of the surface layer throughout the day. Again, calculated LCL values remained too high to form clouds.

3) 19 JUNE 1986—FLIGHT 16

Because this case was the next consecutive flight, the synoptic conditions from both days in between flights 15 and 16 are presented here for better continuity. On 17 June 1986, the cold front backed out to the west, extending from Scotland down along the west coast of France. Skies were overcast over the HAPEX domain, with a stratus deck at 450 – 650 m . Northwesterly flow at 50 kPa was about 5 m s^{-1} in a weak gradient.

The next day at the surface, a 102-kPa high centered over Brittany resulted in a weak NE flow. The cold front passed to the north of the region overnight, stretching from Berlin to Geneva. Aloft, northeasterly flow was observed in a zone of weak gradient. In the

FIG. 6. Joint frequency distributions for each flight segment along track 2 for 9 June 1986 (flight 13). Values are sorted into bins of size 0.1 K (θ_v) by 25 m (z_{LCL}) and are indicated by the tic marks as shown. Contours are at frequency intervals of 0.00001, 0.0001, 0.001, 0.01, and every 0.01 thereafter. Note that all graphs depict the same range in θ_v and z_{LCL} . Segment numbers are given in the upper corner of each graph.

morning, a layer of stratocumulus (base 1200–1500 m) eventually broke up to leave a clear to partly cloudy sky by evening, although the sky was mostly cloudy during the daylight hours.

Finally, the synoptic conditions on the 19th were ideal for our case study. Winds were reported to be nearly calm for much of flight 16 under clear skies. At the surface, a 101-kPa low center was off the coast of Brittany, with a trough extending to Northern Spain. The associated cold front stretched from Southern Ireland to the northwest tip of Spain. A well-organized Atlantic low at 50 kPa centered off the coast of Ireland

produced a southerly flow of 7 m s^{-1} over the site. The sky was initially clear to partly cloudy with localized morning fog. Powerful thunderstorms later developed over the Pyrenees. These storms spread into the HAPEX box during the evening hours. From the flight logs, it was reported that the inversion height rose rapidly from a low of 0.9 km (MSL) to a maximum estimated at 2.4 km late in the day.

A few cumulus briefly formed during this day. Although the LCL heights were well below the inversion for the second track, clouds did not form at this time, implying that the parcels were too cold to rise and form

FIG. 7. Segment 9 of flight 13, track 2. (a) Full 2D JFD, (b) 1D distribution with Z_{LCL} sliced through the 2D peak, and (c) 1D distribution of θ_v through the peak.

clouds. Later in the day, however, a few cumulus clouds formed at the top of this rapidly growing mixed layer, indicating that the surface-layer θ_v had warmed enough to provide sufficient buoyancy for parcels to rise.

Only two tracks of data are available for this case, but each track is complete. The distributions from track 1 show similar characteristics to those from the previous case, flight 15. There had not been any rain over the area since the previous flight, so little change in the character of the distributions would be expected. For track 2, there was little change in the overall ranges of LCL and θ_v , and by this time the rapidly deepening mixed layer would soon be deep enough to allow cumulus formation, as previously discussed.

A rather curious feature, however, was a lowering of the Z_{LCL} with time, while θ_v continued to rise, in segments 10, 11, and 12. As the mixed layer became deeper over the course of the day, one might expect evidence of drying as entrainment of the drier air aloft takes place; instead, the humidity level remained the same based on the aircraft soundings (Fig. 10). Several possible explanations of this observation exist, such as surface evaporation, crop irrigation and transpiration, advection, and entrainment of a moist layer aloft, to name a few. The aircraft soundings rule out the entrainment possibility, and advection seems unlikely due to the light winds observed. However, not enough surface information is available to draw any conclusions for this particular experiment.

4) 2 JULY 1986—FLIGHT 21

The main synoptic feature for this case was a 102.5-kPa high that was centered over the English Channel

the day before, causing a northeasterly flow at the surface. Skies were mostly clear, with the exception of the formation of boundary-layer cumulus during the daylight hours. For the day of flight 21, light southeasterly flow at the surface resulted from the weak pressure gradient. Elsewhere, a cold front extended from Scotland to Brittany. The sky was initially clear and hazy in the lower levels, with 4 to 6 octas of cirrus in the morning which reduced to 2 octas over the course of the day. A low inversion height of 0.5 km (MSL) was observed at the start of the flight, rising to a height of 0.9 km. During the evening, cirrus, altocumulus, and cumulonimbus moved into the area. Thunderstorms passed over the HAPEX domain, with a particularly violent storm at Lubbon, dropping about 50 mm of rain in the vicinity. This rain was noted to be a welcome relief from the previous dry spell.

The segment JFDs for this flight first exhibited some variability, but later began to evolve consistently with each other. Data for the entire first track are available, but segments 6, 7, and 8 are missing from track 2, and 9 through 12 are missing in track 3. For track 1, the range of LCL values is rather large by comparison to the previous cases, ranging from 380 to 1220 m AGL. In fact, segment 4 seems to be caught in some sort of transition. For this case, a combination of a relatively high LCL and low θ_v likely prevented cumulus development.

By track 2, the variability between the segments is more similar to the previous cases presented, and similar characteristics were once again observed. The broad distribution of segment 4, however, did not disappear with time, and continued over the course of the day. This segment is over an area categorized as steep hilly mixed agriculture and given the comments in the synoptic observations about a recent dry spell, it is possible that variations in crop stress and irrigation practices could have contributed to this unusually shaped distribution.

Finally, track 3 exhibited some more unusual distributions and continued the trend on this particular day toward multimodal distributions. As observed in the previous case, a lowering of Z_{LCL} over time was observed in some segments. The segments in question were over various types of farmland (segments 1, 2, 4, and 5), but the data do not allow explanations of this phenomenon.

c. Relationships between different segments

Over the course of a day, individual segment JFDs behaved in a consistent manner with respect to the overall flight average JFD. For example, Table 4 shows the offsets of the modes of the segment JFDs from the JFD mode for the full flight for track 2 of flight 13. This behavior was found for all three tracks of any flight. The relative locations of segment JFDs with respect to the track mean were examined, after the non-stationarity associated with boundary-layer evolution

TABLE 3. Values of $\Delta z_{LCL}/\Delta\theta_v$ ($m K^{-1}$) corresponding to JFD mode positions for each segment of track 1 for each flight and their standard deviations.

Segment	Flight 13	Flight 15	Flight 16	Flight 21	Segment average	Standard deviation
1	116.07	71.43	125.00	137.25	112.44	28.69
2	96.15	94.83	150.00	132.65	118.41	27.40
3	130.43	112.90	150.00	145.35	134.67	16.74
4	86.54	107.14	145.83	121.21	115.18	24.91
5	89.29	116.67	250.00	187.50	160.86	72.41
6	200.00	145.16	178.57	213.41	184.29	29.77
7	321.43	157.41	0.00	189.39	167.06	132.07
8	392.86	120.00	500.00	181.82	298.67	177.93
9	340.91	179.69	150.00	289.47	240.02	90.13
10	227.27	166.67	-250.00	187.50	82.86	223.33
11	250.00	191.67	-187.50	375.00	157.29	242.25
12	138.89	148.44	-83.33	272.73	119.18	148.14

was removed. For example, in flights 13 and 15, the JFD mode for segment 1 was consistently found to have a higher LCL height and warmer θ_v relative to the weighted mean position of the entire flight. By contrast, segment JFDs 11 and 12 exhibited the opposite characteristics of generally lower LCLs and cooler θ_v . Similar patterns were observed in most cases.

Variations in θ_v mean positions were typically quite small (less than 0.5 K), as compared to the overall variation in θ_v for each distribution. Segment 12 was noted to be the most consistent with respect to the track mean, with values that always put it in the lower left quadrant of the graphs. An important implication of these results is that land-use information can indeed be used to help parameterize subgrid variability in temperature and moisture, and hence BLCu.

Neighboring segments generally tended to behave more alike than segments estimated to be of similar landscape category. This may be an indication of the domination of external processes such as advection, or variations of precipitation and soil moisture over larger regions, or it may simply be an artifact of the arbitrary landscape classification scheme used here.

In Fig. 11, the values of z'_{LCL} and θ'_v are plotted for the first five segments of flights 16 and 21. The relative

average positions for each of the segments are very similar on these 2 days. This pattern can also be seen directly in Fig. 12 for flight 16. Here the adjusted segment mean positions have been plotted along with the track mean, with vectors originating from the track mean. Although the scales are slightly different, the relative positioning of each segment remains fairly constant with respect to the track mean, even though the mixed layer is evolving rapidly on this day. This type of consistent behavior is one that could potentially be parameterized and used in a cloud model.

d. Variations of single segments over time

For the cases examined here, approximately 90% of the mean positions increased both in height and in temperature (Fig. 9). This yielded a positive slope of $\Delta z_{LCL}/\Delta\theta_v$ during each flight (Fig. 8) because data were collected during the late morning to midafternoon hours. These increases were slightly nonlinear, with a preference for greater changes in LCL height as the day progressed. This is likely primarily due to a drying of the surface-layer and land surface. As the mixed-layer grows due to entrainment, it is bringing down relatively dry air from the free atmosphere above. This results in a greater change in LCL height than θ_v because the relative warming would be small compared to the drying effect. For those cases where either LCL height or virtual temperature decreased, it is possible that an outside forcing such as advection or crop irrigation was present. Typical changes in LCL height over the course of an entire flight (duration 3 to 4 h) were on the order of 500 m, while θ_v increased an average of 4°C.

Segments 1 through 6 were found to be remarkably consistent in their behavior over the midday hours for all four cases, compared to the remaining segments. These segments had an average $\Delta z_{LCL}/\Delta\theta_v$ of 137 $m K^{-1}$ over the cases examined for track 1 and a standard deviation of 33.3 $m K^{-1}$. These statistics changed as the day progressed, but missing data made comparisons difficult. Upon closer examination of these data,

FIG. 8. Change of height of the lifting condensation level relative changes in the buoyancy over time (from track to track), for each HAPEX flight and each segment. For most segments, the LCL rose currently with an increase in buoyancy of the surface-layer air.

FIG. 9. Joint frequency distributions observed for segment 6 (over flat farmland in a valley) from all three tracks of flight 13. Tic marks indicate sorting bin boundaries. Evolution of the distribution with time is evident by noting changes in the axes from plot to plot. Relative-frequency contour levels are 0.0001, 0.001, 0.01, with additional levels incremented by 0.01.

we suggest that processes such as advection must be considered to accurately determine the effects of the underlying surface.

From day to day, however, the pattern is not as clear. Since the flights were performed several days apart, one would not expect to find a direct relationship because the initial conditions in each case could vary significantly. It is also apparent that the various segments respond to forcing in sometimes radically different manners, as depicted by a shift with respect to the track mean. For example, in direct contrast to section (4c) above, segment 1 is observed to have an LCL that is lower and cooler than the track mean for both flights 16 and 21, the exact opposite from the behavior exhibited in the earlier flights. This suggests that segment 1,

FIG. 10. Specific humidity vertical profiles measured by aircraft slant ascent and descent soundings during flight 16. Legend indicates key points along the flight track where the soundings were made.

determined to be over a farmland–forest transition zone, is perhaps not drying out as rapidly as other portions of the region.

5. Diagnoses of JFD shape parameters

a. Characteristics of the observed JFDs

Although the observed JFDs over individual flight segments from section 4 exhibit a wide variety of shapes, one can identify common features:

- strong central tendency about a single dominant mode (although minor modes can occur)
- sharply pointed peak

TABLE 4. Offset of JFD mode position for each segment from the weighted track average for flight 13, track 2.

Segment	θ'_v	z'_{LCL}
1	0.37	65.18
2	0.22	101.45
3	0.25	-3.58
4	0.25	57.25
5	0.53	29.97
6	0.22	61.95
7	-0.03	-33.21
8	-0.21	-76.31
9	0.16	5.30
10	0.07	-9.64
11	-0.49	-70.73
12	-0.54	-23.86

FIG. 11. The relative differences z'_{LCL} and θ'_v are plotted for flights 16 and 21, segments 1 through 5, for comparison. The origin signifies the track mean.

- spread of the distribution along diagonal axes (theoretically expected from section 2)
- asymmetric tails, causing a skewed distribution (amount and sign of skewness varies from distribution to distribution)
- maximum ranges exist where the frequency becomes zero (i.e., distribution is bounded)
- variation of range with direction from mode, causing an irregular perimeter.

b. Diagnosis procedure

Based on the theory of section 2, we expect that the segment JFDs can be quantified in terms of sloping axes representing Bowen ratio B and solar-forcing temperature θ_F . Figure 13 shows the geometric relationship of the major and minor axes for the JFD. The origin of this graph has been displaced to coincide with the location of the mode (z_{LCLm}, θ_{vm}) of the distribution. To simplify the notation, let $T'' \equiv \theta_v - \theta_{vm}$ and $z'' \equiv z_{LCL} - z_{LCLm}$ represent departures from the mode.

Define b as the slope of the Bowen ratio axis and s as the slope of the solar-forcing axis in the (T'', z'') coordinate system of Fig. 13. As a surrogate for distance along the solar-forcing axis, we will use the projection from the s axis onto the T'' axis and will denote c as the temperature value of this projection. Similarly, m denotes the surrogate height value projected from the b axis onto the z'' axis (Fig. 13). This simplifies the mathematics considerably and can be used with b and s axes of any slopes. Note that while b and s are physically orthogonal, they are not necessarily graphically perpendicular when plotted on the z'' - T'' graph, because the scales along those original axes are arbitrary and not physically related.

Using geometry, any point in (z'', T'') space can be transformed into (m, c) space by

$$m = \frac{T'' - sz''}{b - s} \quad (14a)$$

FIG. 12. Plot of adjusted mean values for each segment for flight 16, tracks 1 and 2, plotted with respect to the overall track mean.

and

$$c = s \frac{T'' - bz''}{s - b}. \quad (14b)$$

This mapping is sketched in Fig. 13.

To objectively determine the Bowen ratio and solar-forcing slopes, a 2D (bivariate) Gaussian distribution is fit to the data. One approach would be to use a distribution framed within the (z'', T'') coordinate system,

FIG. 13. Geometry used to relate any (z'', T'') point (black dot) on the displaced z_{LCL} and virtual potential temperature axes to corresponding coordinates along the sloping Bowen-ratio b and solar-forcing s axes. These new coordinates are represented by their projections (m, c) .

analogous to the distribution discussed by Wyngaard and Moeng (1992). This form uses the covariance between z'' and T'' to tilt the major and minor axes of the distribution. We chose a different form using the (m, c) coordinate system as described next, because the sloping axes have special physical meaning for our problem.

In the (m, c) coordinate system, the bivariate Gaussian distribution can be written as

$$G(m, c) = \frac{1}{2\pi m_{db} c_{ds}} \times \exp \left\{ -0.5 \left[\left(\frac{m}{m_{db}} \right)^2 + \left(\frac{c}{c_{ds}} \right)^2 \right] \right\}, \quad (15)$$

where m_{db} and c_{ds} are the standard deviations along the b and s axes, projected onto the z'' and T'' axes, and measured in units of (m) and (K), respectively.

To statistically estimate the best-fit slopes, a likelihood function L^* can be formed as

$$L^* = -\ln \left[\prod_{i=1}^N G(z_i'', T_i'') \right],$$

where Eqs. (14) are used in (15) to replace $G(m, c)$ with $G(z'', T'')$ and where the product is over each of the N data points (air parcels) along a horizontal flight-leg segment in the surface layer (i.e., i is the air-parcel or data-point index). The parameters that provide the best fit to the observed data are those that maximize the likelihood function, where the maximum is found by setting to zero the first derivative of L^* with respect to each parameter.

For Gaussian standard deviations c_{ds} and m_{db} , the maximum likelihood approach yields

$$c_{ds}^2 = \frac{s^2}{(s-b)^2} [\overline{T''^2} - 2b\overline{z''T''} + b^2\overline{z''^2}] \quad (16a)$$

$$m_{db}^2 = \frac{1}{(s-b)^2} [\overline{T''^2} - 2s\overline{z''T''} + s^2\overline{z''^2}], \quad (16b)$$

where the overbar represents an average over all data points in the flight-leg segment. These averages were computed using the data after it was sorted into bins, rather than the original data; for example,

$$\bar{x} = \frac{\sum f_j x_j}{\sum f_j}, \quad (17)$$

where j is the bin index, f_j is the observed relative frequency of occurrence, and x is an arbitrary variable such as z'' , T'' , or products of these two.

For axes slopes b and s , the maximum-likelihood result after replacing c_{ds}^2 and m_{db}^2 with Eqs. (16) is

$$b = s \left\{ 1 - \frac{2[s^2\overline{z''^2} - 2s\overline{z''T''} + \overline{T''^2}]}{[2s^2\overline{z''^2} - 3s\overline{z''T''} + \overline{T''^2}]} \right\} \quad (18a)$$

$$s = b + \frac{2[b^2\overline{z''^2} - 2b\overline{z''T''} + \overline{T''^2}]}{[\overline{z''T''} - b\overline{z''^2}]}. \quad (18b)$$

Equations (18) can be easily iterated to solve for s and b . Namely, guess b , such as $b = 1$ ($^\circ\text{C}/\text{m}$). Then plug b into (18b) to find s , and use that s in (18a) to find a new b . This iteration is stable and independent of the initial guess and quickly converges toward the answer with five decimal-place accuracy in 10 iterations. Knowing the final s and b , Eqs. (16) can then be solved.

c. Illustration

To illustrate the statistical process of fitting the observed distributions, we use HAPEX aircraft data from flight 15, track 1, segments 4 and 9 (Figs. 14a,b, respectively). This was flown over steep, hilly, mixed agriculture during 9 May 1986. The 5220 data points measured during this flight segment were sorted into bins of width $\Delta z_{LCL} = 25$ m and $\Delta \theta_v = 0.1$ K. The location of any one bin center is (z_j, θ_j) , and the normalized amplitude at that center is f_j . The resulting JFD is shown in Fig. 14a as a contour plot. The complexity exhibited by this distribution was typical and served as a rigorous test of our statistical procedures.

Using the data of Fig. 14a, the best-fit axes slopes are $b = -0.00011$ K m $^{-1}$ and $s = -0.07899$ K m $^{-1}$,

FIG. 14. Example of statistical fit to observed JFDs for HAPEX flight 15, track 1. Observations in (a) and (b) are for segments 4 and 9, respectively. Panels (c) and (d) show the corresponding best-fit axes slopes and statistical spreads as represented by the bivariate Gaussian distributions. Contours are 0.0001, 0.001, 0.01, and increments of 0.01 thereafter. A sorting bin is of size $\Delta z_{LCL} = 25$ m and $\Delta \theta_v = 0.1$ K. Panel (b) also shows the slope of the theoretical solar forcing lines from Fig. 2 or Eq. (13).

FIG. 15. Best fit values of slope s of solar-forcing axis of the JFD, as a function of time for each flight segment. Line patterns in the graph and legend match those of Fig. 5. Time axis is not linear and is plotted in Julian days. Days 160, 167, 170, and 183 correspond to the four clear-sky cases.

with standard deviations of $m_{db} = 62.1$ m and $c_{ds} = 0.186$ K. These four parameters, together with the mode location at $z_{LCLm} = 1137.5$ m and $\theta_{um} = 298.05$ K, fully determine the Gaussian distribution, plotted in Fig. 14c. As another example, Fig. 14b shows the observed JFD for segment 9 of the same flight and track, while Fig. 14d shows the best fit distribution.

d. Discussion of diagnosed JFD parameters

Table A2 in the appendix lists the best-fit parameters that were found for each of the cloud-free HAPEX flight segments discussed in section 4. Of most interest here are the slopes (b , s) of the Bowen-ratio and solar-forcing axes.

Figure 15 shows the variation of slope s of the solar forcing axis over each segment during the course of the field program, based on the best-fit statistics described

FIG. 16. Same as Fig. 15 but for slope b of Bowen-ratio axis.

previously. Magnitudes are on the order of 0.1 to 1.0, with most observations having the smaller magnitudes.

If we assume that the solar-forcing axis follows a constant Bowen ratio line such as plotted in Fig. 2, then we can rearrange (12b) from section 2 to estimate Bowen ratios from solar-forcing slope s :

$$B \approx \frac{B_0}{1 - 1/as}, \quad (19)$$

where $a = 125$ m K⁻¹ and $B_0 = 0.741$. Table 5 shows the resulting Bowen ratios for each segment, averaged over the first 3 clear days (flights 13, 15, and 16). These values are mostly in the range of 0.6 to 0.9, which fall well with the range of Bowen ratios (0.3–1.3) measured directly by aircraft and by the surface energy-budget stations during that same time period (André et al. 1990). André also reported a relative maximum of Bowen ratio over the forest, which agrees with our findings.

During the fourth clear day (flight 21), the surface was apparently drier, causing much smaller values of s and larger values of Bowen ratio. Some of the s values were near the critical value of $s = 1/a = 0.008$, for which Eq. (19) is no longer valid. During the second clear day (flight 15), some of the s values were infinite, which implies a horizontal line in (z'' , T'') space with $B = B_0 \approx 0.74$. These latter values are quite reasonable.

Figure 16 shows the variation of the slope b of the Bowen ratio axis over each segment during the course of the field program, based on the best-fit statistics described previously. This slope should be orthogonal to a line of constant Bowen ratio. From the previous discussion we found typical Bowen ratios of about 0.7, which is nearly horizontal in Fig. 2. Thus, an orthogonal line would be nearly vertical. Indeed, the relatively small magnitudes of b (order of 0.001 K m⁻¹) plotted in Fig. 16 implies an axis that is close to vertical in (z'' , T'') space.

TABLE 5. Bowen ratio B for each segment estimated from best-fit slope s of the insolation axis, averaged over the first 3 clear days of data.

Segment	Surface	Bowen ratio
1	Flat farm–forest transition	0.8
2	Steep hilly mixed agriculture	0.9
3	Moderate hilly mixed agriculture	0.8
4	Steep hilly mixed agriculture	0.7
5	Flat farmland	0.6
6	Flat farmland	0.8
7	Moderate hilly mixed agriculture	0.7
8	Flat farm–forest transition	0.8
9	Flat forest	0.9
10	Flat farm–forest transition	0.8
11	Moderate hilly mixed agriculture	0.7
12	Flat farmland	0.7

The slopes of the solar forcing lines, such as plotted in Fig. 2, are expected to be approximately 0.0046 K m^{-1} , based on Eq. (13b). A line of this slope is plotted in segment 9 (forest) of Fig. 14b. The Landes forest in the HAPEX field region is a relatively homogeneous planted pine forest of 19 m average height. From the arguments in section 2, we expect a surface with uniform forcing temperature such as the forest to have a JFD that is spread along a line of constant θ_F (see Fig. 2). However, this slope was not consistent from track to track, as is evident in Table A2.

By comparing the shapes of the segment JFDs from Fig. 6 with the theory of Fig. 2, we see that a vertically spread JFD implies that weak solar forcing is correlated with high Bowen ratio, in a relative sense, and strong solar forcing with low Bowen ratio. Such a correlation can be anticipated because lush vegetated regions are likely darker colored than neighboring dry pasture. This observation also highlights the dominant role of precipitation and soil moisture on determining the shapes of the JFDs. During the HAPEX field program, there were frequently scattered showers that dampened the soil in only portion of the HAPEX region. Thus, a more precise intercomparison of the JFD shapes with surface characteristics would require more localized precipitation and vegetation information than was recorded during HAPEX.

6. Conclusions

Observations of landscapes in the HAPEX domain of southwest France indicate that subdomains of somewhat uniform land use can be identified. The Landes forest is just one example. These subdomains are typically of order 10–20 km in size, which are larger than an individual field or copse and larger than typical thermal diameters. Although the mean wind and turbulent mixed layer tends to blend the atmospheric effects of the various farm fields within any one subdomain, there are nonetheless differences from subdomain to subdomain.

Within any one subdomain, however, landscapes and atmospheric characteristics are not perfectly uniform. Within the surface layer of such a subdomain, one expects a range of temperatures and humidities clustered about the subdomain average. From these attributes, one can calculate ranges of virtual potential temperature θ_v and lifting condensation level LCL, two variables that describe the potential for cumulus clouds to form in the mixed layer. These variables are not independent, because they both depend on the nature of the surface and the total energy input from the sun. Hence, the relationship between these variables can be quantified using a joint frequency distribution.

A theory is developed to explain the shape of the joint frequency distribution of LCL versus θ_v in

surface-layer air, as a function of surface Bowen ratio and solar forcing. These forcings are controlled by landscape, insolation, surface albedo, cloud shading, soil moisture, and other factors. We have nicknamed this the “bigfoot theory” because some of the first JFDs we tested it on looked like footprints.

Aircraft data obtained during cloud-free days during the HAPEX 1986 intensive operation period are used to measure the JFD for surface-layer air. The flight track is broken into shorter segments, corresponding to the land-use subdomains. The influence of Bowen ratio and solar forcings on these segment distributions are found by a maximum-likelihood estimation of the axes and standard deviations of a bivariate Gaussian distribution best fit to the data. For any one segment, typical standard deviations of the JFD are on the order of 50 m for LCL and 0.25 K for θ_v . However, the range of the distributions are typically ± 200 m about the mean LCL and ± 1 K about the mean θ_v . Details for individual segments are given in Table A2.

Although the mean LCL and θ_v for the whole HAPEX region evolves with time during any day, the relative location of a segment JFD from that of the whole track exhibits somewhat similar behavior from day to day. Namely, those segments with below average LCL and θ_v on one day are likely to have similar deviation on other similar (clear sky) days. This suggests the possibility that the gross description of the subdomain landscape can be used to quantify the location of the corresponding JFD. On a smaller scale, however, the shape of the JFD for any one subdomain seems to vary somewhat unpredictably, but might be a function of heterogeneous soil moisture and precipitation events that were not adequately documented during HAPEX. On the average, however, the slopes of the segment JFDs are about what would be expected from the bigfoot theory.

This study was motivated by the need to forecast subgrid-scale boundary-layer cumulus clouds in global climate models and in 1D (single column) forecast models. Our quantification of JFDs for this case study is just a first step toward understanding the bigger problem boundary-layer cumulus over land. We are continuing the research to show how cloud shading modulates the surface heterogeneity and how the JFDs can be used to predict cumulus cloud onset time, coverage evolution, and cloud ensemble size distributions. This work is being extended, using data from the Department of Energy Atmospheric Radiation Measurement program CART site in Oklahoma. In addition, older datasets such as from the BLX83 experiment will be reexamined using the methods described here and compared with the cloud forecasting techniques previously described by Wilde et al. (1985) and Wetzel (1990).

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APPENDIX

Supporting Information

a. Bowen parameter

The term $B_{ML} = (\gamma/r_{ML})(T_{dML}^2/c_p)$ as used in Eq. (7) varies with dewpoint as plotted in Fig. A1.

b. Lyman-alpha calibration

Although care was taken to properly calibrate the instruments before and after each flight, additional

FIG. A1. Variation of the parameter B_{ML} as a function of dewpoint temperature T_d for two pressures P .

TABLE A1. Parameter values and constants used in calibration of the Lyman-alpha hygrometer (Eloranta et al. 1989). STP is standard temperature and pressure.

Parameter	Value	Description
e_s	0.622 kPa	Saturation vapor pressure at STP
R_w	$0.461 \text{ J g}^{-1} \text{ K}^{-1}$	Gas constant for water vapor
T_{stp}	273.16 K	Standard temperature at sea level
P_{stp}	101.325 kPa	Standard sea level pressure
k_{H_2O}	387.0 cm^{-1}	Absorption cross section of water
k_{O_2}	0.81 cm^{-1}	Measured absorption cross section of oxygen
x	0.46 cm	Effective path length for the right Lyman-alpha probe
c_1	0.4605 V^{-1}	Amplifier constant
c_2	0.2315	Mass fraction of oxygen in air

calibration of the data was performed to convert output voltages into absolute humidity values. By comparing the two airborne Lyman-alpha hygrometers with the airborne dewpoint hygrometer and ground-based calibrations, it was determined that the Lyman-alpha probe mounted on the right-hand side of the aircraft was the most accurate. Calibration of this hygrometer was performed separately for each flight segment to remove drift of the instrument characteristics during flight, following the procedures outlined by Eloranta et al. (1989). First, leg mean values of voltage V , temperature, and pressure were used to calculate a mean reference voltage V_0 for each flight leg. Then the instantaneous values of V were used to calculate the turbulent absolute humidity at each point. Table A1 lists the parameters and constants used in the equations defined by Eloranta et al. (1989).

c. JFD statistics

Best-fit JFD statistics for each flight segment are listed in Table A2. To measure the goodness of fit, a total error is computed for each segment as

$$\text{err} = \sum_j |fm_j - fd_j|,$$

where fm is the parameterized [modeled using Eq. (18)] frequency, fd is the observed frequency, and j is the 2D bin index. A Gaussian model that matches the observations perfectly would give zero error. A uniform model of zero distribution everywhere (i.e., a nonmodel) would give error equal to 1.0, which is the normalized integral under the observed JFD. It is expected that the model errors should be between zero and unity, although an especially bad model could have error greater than 1.0. Because the JFDs are normalized, this error can also be interpreted as a relative error.

TABLE A2. Observed statistics and best-fit model parameters for each HAPEX flight segment. Point count is the number of 20 Hz observations per flight segment. Symbol z is the height of the lifting condensation level, and T is the virtual potential temperature for air in the surface layer. Other symbols are defined in the text.

Flight ID			Data	HAPEX							
Flight Track Seg				Mode			Axes Slopes		Standard Dev		Err
				z (m)	T (K)	freq.	b (K/m)	s (K/m)	m db (m)	c ds (K)	
13	1	1	1900	1362.5	294.05	0.078	0.00032	0.03290	58.7	0.190	0.575
		2	4600	1462.5	294.05	0.071	0.00010	0.10706	62.1	0.207	0.552
		3	1040	1337.5	294.25	0.069	-0.00044	-0.03305	43.8	0.168	0.506
		4	5560	1437.5	294.05	0.063	-0.00036	-0.02047	81.9	0.222	0.750
		5	500	1387.5	294.15	0.196	-0.00043	-0.03456	42.5	0.163	0.667
		6	1960	1387.5	294.25	0.071	0.00067	0.02611	59.2	0.248	0.676
	2	1	1140	1687.5	296.85	0.086	-0.00090	-0.09377	33.7	0.309	0.617
		2	4060	1712.5	296.65	0.083	-0.00146	-0.04798	40.0	0.335	0.498
		3	960	1612.5	296.65	0.141	0.00029	0.05280	38.8	0.151	0.679
		4	4880	1662.5	296.65	0.054	-0.00036	-0.02383	70.1	0.205	0.534
		5	20	1637.5	296.95	0.300	-0.00083	-0.06981	12.3	0.093	0.508
		6	2260	1662.5	296.45	0.077	-0.00046	-0.02614	67.5	0.233	0.795
		7	8680	1562.5	296.15	0.043	-0.00057	-0.07495	44.3	0.289	0.415
		8	3360	1512.5	295.95	0.060	0.00047	0.05743	61.0	0.315	0.755
		9	6780	1537.5	296.15	0.034	0.00076	0.05047	63.5	0.393	0.604
		10	1380	1537.5	296.05	0.106	0.00311	0.03486	36.7	0.382	1.077
		11	4620	1462.5	295.45	0.063	0.00049	0.02959	78.5	0.298	0.865
		12	2260	1537.5	295.45	0.105	0.00011	0.35192	43.0	0.261	0.643
	3	6	1960	1762.5	296.95	0.148	0.00039	0.04366	65.5	0.271	0.860
		7	8180	1787.5	296.85	0.043	-0.00020	-0.10338	55.1	0.252	0.391
		8	3860	1787.5	296.65	0.049	0.00104	0.04893	55.6	0.396	0.767
		9	4760	1912.5	297.25	0.059	-0.00039	-0.13462	49.1	0.355	0.704
		10	1400	1787.5	297.15	0.141	0.00117	0.04408	44.3	0.318	0.887
		11	4420	1762.5	296.65	0.045	-0.00028	-0.05602	91.4	0.364	0.760
	12	2360	1662.5	296.35	0.059	0.00067	0.03674	72.3	0.359	1.050	
15	1	1	2360	1237.5	298.15	0.135	0.00019	0.14482	38.7	0.202	0.607
		2	4460	1162.5	298.15	0.071	0.00022	0.05666	53.8	0.191	0.448
		3	1060	1087.5	297.95	0.106	0.00086	0.02141	57.2	0.245	0.718
		4	5220	1137.5	298.05	0.075	-0.00011	-0.07899	62.1	0.186	0.490
		5	700	1037.5	297.85	0.090	0.00010	0.05633	50.8	0.119	0.471
		6	2600	1037.5	297.45	0.110	0.00147	0.03092	33.1	0.223	0.560
		7	8020	1037.5	297.45	0.068	0.00054	0.04397	47.6	0.231	0.652
		8	2620	1062.5	297.65	0.084	0.00072	0.11835	27.0	0.250	0.383
		9	6420	1087.5	297.75	0.037	0.00159	0.01965	66.6	0.372	0.714
		10	1400	1162.5	297.75	0.113	0.00530	0.09207	20.4	0.451	0.678
		11	4240	1087.5	297.65	0.047	0.00046	0.11690	44.6	0.328	0.618
		12	1540	1187.5	296.95	0.095	0.00152	0.05003	40.5	0.353	0.760
	2	1	1460	1437.5	300.95	0.429	0.00000	∞	0.0	0.297	0.587
		2	4040	1437.5	301.05	0.281	0.00000	∞	0.0	0.236	0.221
		3	960	1437.5	301.05	0.352	0.00000	∞	0.0	0.193	0.464
		4	5000	1437.5	300.85	0.266	-0.00106	-0.13660	15.2	0.182	0.488
		5	240	1387.5	300.85	0.175	-0.00129	-0.02819	27.7	0.167	0.826
		6	2460	1487.5	300.55	0.212	-0.00134	-0.32612	14.7	0.308	0.530
		7	8260	1462.5	300.15	0.045	-0.00026	-0.05261	71.2	0.265	0.511
		8	3380	1362.5	300.15	0.071	0.00035	0.09740	46.2	0.271	0.650
	3	3	110	1487.5	301.25	0.518	0.00000	∞	0.0	0.107	0.186
		4	5240	1487.5	301.15	0.408	-0.00591	-2.11798	1.9	0.211	0.480
		5	1100	1487.5	301.15	0.306	-0.00346	-0.16631	10.5	0.252	0.468
		6	3237	1562.5	300.95	0.222	0.00114	0.38027	11.7	0.244	0.510
		7	8280	1587.5	300.75	0.060	-0.00149	-0.02928	50.6	0.334	0.670
		8	2956	1562.5	300.85	0.083	-0.00047	-0.10517	57.1	0.400	0.686
		9	5396	1662.5	300.95	0.052	-0.00066	-0.05456	65.6	0.393	0.573
		10	1300	1662.5	300.75	0.166	-0.00156	-0.11260	29.6	0.392	0.566
		11	4140	1662.5	300.65	0.066	-0.00005	-0.15614	86.2	0.247	0.519
		12	1060	1662.5	300.15	0.226	-0.00134	-0.03375	40.3	0.271	0.764

TABLE A2. (Continued)

Flight ID			Data	HAPEX									
Flight Track Seg				Point Count	Mode			Axes Slopes		Standard Dev		Err	
				z (m)	T (K)	freq.	b (K/m)	s (K/m)	m db (m)	c ds (K)			
16	1	1	1060	1387.5	302.55	0.099	0.00091	0.12409	27.6	0.293	0.633		
		2	4380	1437.5	303.05	0.155	0.00017	0.37943	28.4	0.225	0.623		
		3	1060	1437.5	303.25	0.323	-0.00100	-0.24192	10.2	0.158	0.394		
		4	5140	1437.5	303.45	0.189	-0.00100	-0.47905	13.6	0.297	0.438		
		5	660	1437.5	303.95	0.152	-0.00089	-0.03224	34.2	0.183	0.471		
		6	1890	1512.5	303.95	0.154	-0.00147	-1.27020	7.0	0.304	0.453		
		7	4360	1587.5	303.25	0.093	-0.00076	-0.01887	66.3	0.250	0.756		
		8	3220	1562.5	303.85	0.058	0.00124	0.05170	54.9	0.439	0.806		
		9	6500	1562.5	303.75	0.050	0.00127	0.02895	62.6	0.379	0.791		
		10	1380	1387.5	303.25	0.100	0.00098	0.04784	32.5	0.223	0.541		
		11	4380	1462.5	302.45	0.078	-0.00105	-0.01739	69.1	0.296	0.827		
		12	1160	1487.5	302.05	0.125	-0.00080	-0.02437	36.4	0.161	0.576		
	2	6	2860	1637.5	304.65	0.057	0.00101	0.04159	41.3	0.268	0.576		
		7	8280	1587.5	303.85	0.051	-0.00051	-0.07851	47.5	0.300	0.551		
		8	3160	1612.5	303.95	0.063	0.00176	0.06329	38.2	0.403	0.671		
		9	6360	1662.5	304.15	0.050	0.00047	0.05385	64.3	0.322	0.592		
		10	1340	1412.5	303.15	0.054	0.00210	0.11211	37.8	0.579	0.679		
		11	4440	1387.5	302.85	0.032	-0.00052	-0.01853	89.0	0.276	0.726		
	3	12	1280	1462.5	302.35	0.093	-0.00084	-0.02727	48.7	0.233	0.886		
		1	1340	1487.5	303.35	0.124	-0.00165	-0.08636	23.0	0.275	0.588		
		2	4260	1587.5	304.05	0.068	0.00055	0.01763	71.1	0.222	0.625		
		3	1020	1587.5	304.25	0.100	-0.00077	-0.01663	49.9	0.179	0.679		
		4	5140	1612.5	304.65	0.072	0.00029	0.06799	53.4	0.238	0.696		
	1	5	760	1662.5	304.85	0.175	-0.00054	-0.01347	45.1	0.122	0.712		
		1	1480	437.5	297.45	0.170	0.00201	0.07930	25.0	0.315	0.768		
		2	4420	437.5	297.75	0.058	0.00247	0.02287	52.9	0.398	0.704		
		3	1060	487.5	298.55	0.154	0.00064	0.13959	27.6	0.260	0.592		
		4	5240	812.5	299.95	0.026	0.00218	0.01040	178.5	0.850	1.358		
		5	1060	762.5	299.85	0.087	0.00002	0.15732	79.1	0.128	0.784		
		6	2720	762.5	300.25	0.069	0.00123	0.05519	29.7	0.245	0.671		
		7	8399	962.5	300.55	0.037	0.00087	0.00576	147.4	0.330	1.059		
		8	3200	962.5	300.55	0.118	-0.00043	-0.02042	36.2	0.107	0.359		
		9	6380	937.5	300.85	0.069	0.00111	0.01236	73.3	0.271	0.796		
		10	1377	1112.5	301.05	0.079	0.00001	3.59678	56.5	0.306	0.784		
		11	4320	1037.5	300.85	0.052	-0.00008	-0.29136	47.5	0.234	0.578		
		12	1180	837.5	300.25	0.098	0.00093	0.00793	79.1	0.215	1.054		
	2	1	1380	1137.5	302.55	0.043	0.00024	0.03263	83.0	0.234	0.770		
		2	3980	1087.5	302.55	0.062	0.00049	0.01475	98.7	0.267	0.903		
		3	1020	1112.5	302.85	0.109	0.00099	0.02632	43.6	0.222	0.936		
		4	4940	1212.5	303.25	0.033	0.00089	0.00617	160.7	0.377	1.172		
		5	620	1512.5	303.85	0.150	-0.00038	-0.02591	46.7	0.147	0.686		
		9	7352	1487.5	302.75	0.055	-0.00040	-0.07070	78.1	0.418	0.838		
		10	1400	1412.5	302.65	0.066	0.00092	0.02987	59.1	0.310	0.721		
		11	4620	1337.5	301.65	0.050	-0.00196	-0.01626	95.6	0.539	0.942		
		12	1460	1137.5	301.35	0.110	0.00082	0.00843	100.1	0.264	1.096		
			3	1	1140	1037.5	302.85	0.078	0.00034	0.02244	88.0	0.243	1.032
				2	4340	1037.5	303.05	0.038	0.00029	0.00874	156.8	0.248	0.909
				3	1000	1237.5	303.45	0.095	-0.00047	-0.01431	66.8	0.174	0.761
4	5160			1187.5	303.45	0.028	0.00116	0.00653	199.3	0.550	1.081		
5	1020			1437.5	304.45	0.106	0.00044	0.00995	93.9	0.196	0.941		
6	2547			1637.5	304.35	0.092	0.00016	0.18769	60.0	0.334	0.775		
7	8515			1587.5	303.85	0.038	0.00084	0.02438	93.5	0.424	0.879		
8	1860			1562.5	303.85	0.064	0.00003	0.32097	67.1	0.202	0.753		

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