INSIDE THERMALS

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ABSTRACT

Conditional sampling is used to locate mixed layer thermals and surface layer plumes, as well as their downward moving companions - downdrafts - in a large data set obtained from flights by an instrumented motorglider in convective boundary layers over Eyre Peninsula, South Australia. The high resolution and excellent spatial coverage of the data permits a detailed study of internal structure. A compositing technique is used to construct average intersections through thermals and plumes from aircraft runs of given heights and directions. Groups of composites are then combined to form horizontal and vertical cross-sections, revealing the flow patterns and distribution of physical variables within "typical" thermals and plumes and their environment. Surface layer plumes are found to have strong lateral inflow patterns, in which air from the horizontal plane channels around the sides and then in behind the microfront present at the upstream edge. Mixed layer thermal towers have a relatively simple form, consisting primarily of large columns of warm, upwards moving turbulent air, which may occasionally be in a

state of slow clockwise rotation. Finally, the results of this study are combined into a schematic composite depicting the highly complex interactions between the convective plumes of the surface layer and the thermal towers of the mixed layer.

1. INTRODUCTION

During clear-sky days over land, solar illumination of the earth's surface causes warming of the lowest layers of the atmosphere. The subsequent motion of convective eddies causes the breakdown of the shallow nocturnal boundary layer, which is then replaced by a rapidly growing, inversion-capped convective boundary layer (CBL), which may reach heights of up to 2-3 km. Within this highly turbulent region can be identified two layers with distinctly different characteristics: In the lowest tenth of the CBL, is the surface layer (SL), which is characterized by a superadiabatic lapse rate and strong wind shear associated with closeness to the ground. Processes within this layer are dominated by the proximity of the surface and its associated degree of roughness. The remainder of the CBL is known as the mixed layer (ML), in which the properties of the surface play a smaller role, and thermal convection is the major driving force for vertical air movements. Here, there is often little or no wind shear, and the area-averaged values of potential temperature and humidity are nearly constant with height.

The two most common types of well-defined turbulence elements or structured eddies present in the CBL are surface layer plumes and mixed layer thermals. These phenomena provide the major mechanisms for the transport of heat and moisture away from the earth's surface, and they are what glider pilots summarizing call "thermals." In the following paragraphs, we will give a short overview of what is currently known about their shape and size. In the main part of this paper we will then present typical horizontal and vertical cross sections of surface layer plumes and mixed layer thermals derived as composites from aircraft traverses.

Surface layer plumes are travelling flow structures extending throughout the depth of the SL and sometimes beyond (up to 20% of the distance to the inversion; Williams, 1991). They have horizontal dimensions of the order of 100m, and are transported in the mean wind direction at speeds roughly equal to that of the mean wind at their mid-heights (Kaimal and Businger, 1970; Kaimal, 1974; Wilczak and Tillman, 1980). The presence of wind hear through the SL thus dictates that plumes will be moving faster than the mean wind close to the surface. This, however, does not imply that air within plumes is moving faster than the mean wind. In fact, the opposite is true, since plume air is always rising into regions of greater momentum (due to the wind shear). The plume acts in a manner analogous to a vacuum cleaner, scooping up the warm surface air as it moves forward through it. Relative to the plume, the surface air flows underneath its leading edge, and then peels upwards at the trailing edge. This is similar to air motion at the base of small cumulus clouds (Telford, 1986). The interception of warm, lower momentum air from below with the cooler, faster air it rises through, sets up a microfront at the upwind edge of plumes. These microfronts are manifest in SL temperature records from towers, as asymmetric "ramp" shapes (See, for example, Antonia et al., 1979).

Owing to their limited height above ground, meteorological towers can only provide measurements for the lowest parts of the mixed layer, and it is mainly for this reason that the detailed form of thermals is not as well known as that of their SL cousins, the surface layer plumes. Only in recent years, has the technology become available enabling scientists on the ground to sample mixed layer structures at different heights and positions simultaneously. This technology has come in the form of high-powered radars and lidars, and is backed up by the development of more and more sophisticated laboratory and computer models. While it is clear that great variability exists from thermal to thermal, it is now certain that they are greatly elongated in the vertical, often extending throughout the mixed layer in the form of thermal "towers." The air within these columns is warm and buoyant in the lower part of the ML, but often loses its buoyancy in the upper ML, owing to mixing of warmer air from above the inversion into the areas between thermal momentum, however, is still sufficient to carry it to the inversion, where it penetrates briefly into the smoothly flowing air above, before falling back into the boundary layer to complete the circulation.

With the exception of a small amount of turbulent entrainment at their edges, there is little exchange of air between thermal towers and the slow, wide downdrafts between them in the mixed layer. The regions of cross-flow that must exist in order to complete the circulation are at the top and base of the columns. At the base, this is the mechanism by which the warm SL air is transported into the ML, and processes in the transitional region between the layers can become quite complex. Thermal towers, therefore, contain air originating in the surface layer, including the turbulent and contorted remains of SL plumes. Computer models (Schmidt and Schumann, 1989) have recently suggested that these form "bubbles" of exceptionally warm (and therefore highly buoyant) air, which may remain intact for long periods. Since they would travel upwards faster than the rest of the column, an object carried within them would also rise at a greater rate than normal. This might explain why gliders joining thermals below other gliders circling high above can sometimes catch up with the ones higher up.

Although plumes and thermals have been studied by scientists for a number of years, there are still several important aspects of their form and behavior which are little understood. One of these is their internal structure in three dimensions. Little detail is presently known regarding the flow fields and distribution of important physical quantities within and immediately adjacent to plumes and thermals, and of the few studies that have appeared on this subject, most have concentrated upon along-wind profiles of surface layer plumes from tower data. Information is lacking regarding the across-wind structure of surface layer plumes and most aspects of the structure of mixed layer thermals.

2. Aircraft, Experiments and Data Processing

The research aircraft used as the instrumentation and data logging platform for this study was a Grob G-109B motorglider, operated by the Flinders Institute for Atmospheric and Marine Sciences (FIAMS). The aircraft is equipped with a comprehensive set of fast and sensitive meteorological instruments, supported by a sophisticated data acquisition and "real time" processing system. Most sensors are mounted in or on the instrument container: a "pod" attached under the left wing of the aircraft. A full description of the aircraft's equipment and instrumentation, as well as its specifications and capabilities, can be found in Hacker and Schwerdtfeger (1988).

Data were collected in South Australia during the driest part of summer (January to March, 1988) over Hincks Conservation Park and surrounding areas of the semi-arid central Eyre Peninsula (approx. 33 degrees 45" S/135 degrees 50" E). Covering an area of about 700-1000 km, Hincks Park is a region of native mallee bushland surrounded by vast areas of cleared agricultural land. The average height of the mallee vegetation is about 2-4m.

During six days, series of "L" shaped legs were flown at several heights over both agricultural land and the conservation park. Ascents and descents were also flown in order to establish the height and basic structure of the boundary layer. Two ground stations were operated continuously during the times of the flights, recording basic meteorological parameters, including profiles of temperature, humidity, wind speed and direction. Air pressure, net radiation and cloud conditions were also tabled. A total of 102 runs were selected for use in the present study. The total flight length of data used is around 1250 km.

A conditional sampling approach was adopted in order to locate thermals and plumes in the data. As buoyancy (i.e. density less than that of the ambient air) is the most pronounced indicator for thermals, we chose the virtual potential temperature, θ_v , as the primary indicator series. Virtual potential temperature is defined as $\theta_v = \theta\,(1+0.61r)$, where r is the water vapor mixing ratio and θ the potential temperature ($\theta = T(p_o/p)^{0.286}$, where T is air temperature, p is air pressure and p_o = 1000hPa). θ_v is inversely proportional to density and is thus a direct measure of the buoyancy of air parcels. Additionally, we then selected only those parts of the time series which had an upwards air movement. A plume/thermal was thus defined as a section in the time series, in which θ_v exceeded a certain threshold value and where w_{air}, the vertical speed of the air, was positive. Such a section will also be denoted "warm up" in the following. Using the opposite criteria to those used for the "warm up" sections, the negatively buoyant downdrafts (denoted "cool down") that occur between plumes and thermals were also located in order to study their structure as well.

The "average" internal structure of the "warm up" and "cool down" events sampled was determined in the following way. For each run flown along a particular direction at a given height, the data from all the plumes/thermals located by the conditional sampling analysis were extracted in segments. These segments were then "stretched" to equal lengths, overlayed and averaged together, to produce a composite intersection through a "typical" event for that height and direction. Figure 1 shows this process in diagrammatic form.

3. Horizontal Cross-Sections

All the "composites" falling in similar height and direction groups were combined together, and plotted into two-dimensional cross-sections, representing the flow patterns and the distribution of physical quantities associated with a "typical" structure and its immediate environment. Horizontal cross-sections will now be presented, showing the three-component wind field in a horizontal plane surrounding the structure, with the mean wind vector subtracted. The two horizontal wind components are plotted as arrows with the velocity scale indicated to the side of the diagram. The up-page direction represents the direction of the mean horizontal wind. The vertical velocity is represented by a series of contours, plotted on top of the arrows (solid for positive values, dotted for negative). All results are presented in scaled form which means that all variables are divided ("scaled") by certain scaling parameters to eliminate the effects of different depths of the CBL, roughness of the ground, buoyancy and mean wind profile. A reader unfamiliar with scaling can easily translate the axes of the cross-sections, as well as the contours and arrows, into "real" units by choosing typical values for the scaling parameters. For a mid-latitude summer day with

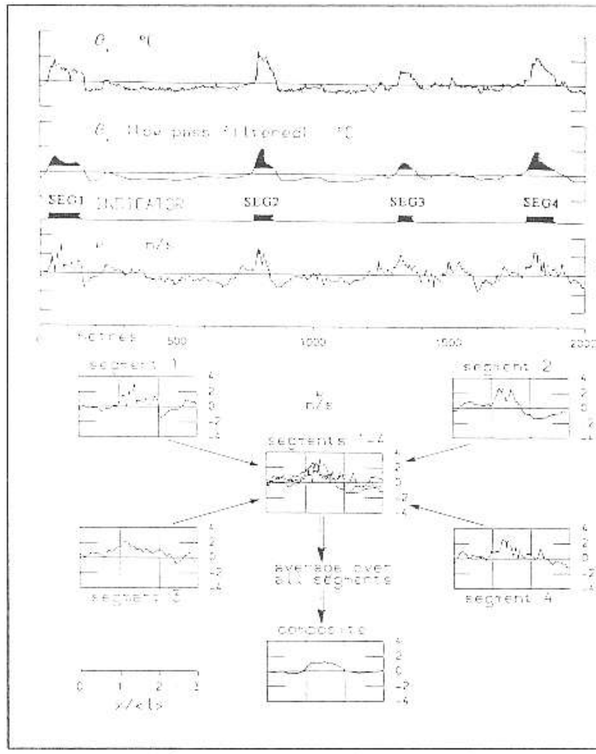

FIGURE 1. A diagrammatic explanation of the compositing method for "warm up" events. For each physical variable, the time series segments corresponding to events defined in the indicator are "cut out" and stretched to a constant number of data points. An equal length on either side of each segment is included in order to represent its immediate environment. Averaging is then performed across corresponding data points of all events, to produce the final composite.

moderate winds, the following values are typical: u_* (friction velocity) = 0.3-0.6 m/s; L (surface layer depth) = 20-100m; w_* (mixed layer scaling velocity) = 1-2 m/s; Z_i (CBL inversion height) = 500-2000m.

Figures 2 to 8 show horizontal cross-sections through composite structures at different heights above the ground. Starting near the ground, Figures 2 and 3 show an increase of surface layer plume size with height, accompanied by a change from along-wind to lateral elongation. A ominant and most interesting feature is the lateral inflow into the plume, which occurs strongly at both levels. To the sides and upwind of the central updraft, are regions of fast moving air, which, at the flanks, turn inwards, feeding cool, high momentum air into the center of the plume. In the along-wind direction, the upwards movement of flower air from below is evident in a long band, starting at the center of the plume and extending, in a weakening form, all the way to the downwind end of the picture. The strength of this band of air reduces with height. The air with the slowest horizontal speed is at the very center of the picture, which is also the region of fastest upwards motion. At the upwind edge of the plume is seen the region of micro-frontal development, with strong convergence in both horizontal directions and stretching in the vertical direction.

The corresponding downdraft cross-sections are shown in Figures 4 and 5. These reveal a pattern of outflow at both levels over an area larger and less elongated than the plume, with broad, weak downward flow in the center. In the region corresponding to the microfront on the "warm up" pictures, is a line of weakly divergent flow, orientated in the across-

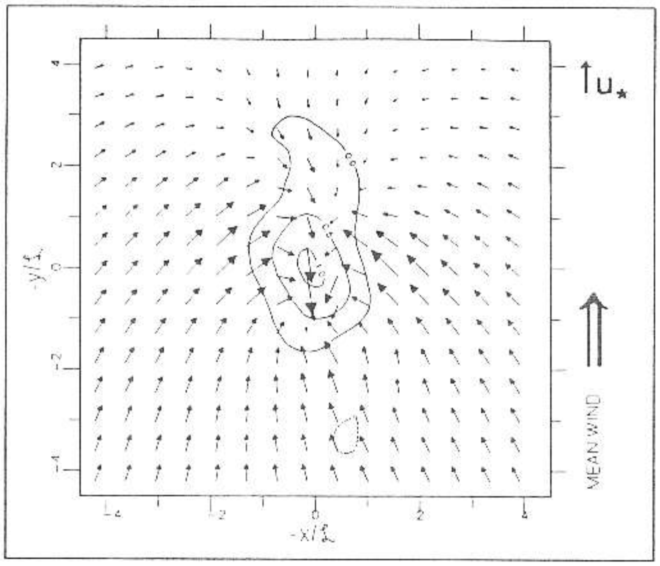

FIGURE 2. Horizontal cross-section for "warm-up" structure in the surface layer for $-z/L = 0.2 - 0.7$. Mean wind direction is up the page. Contours are w/u.

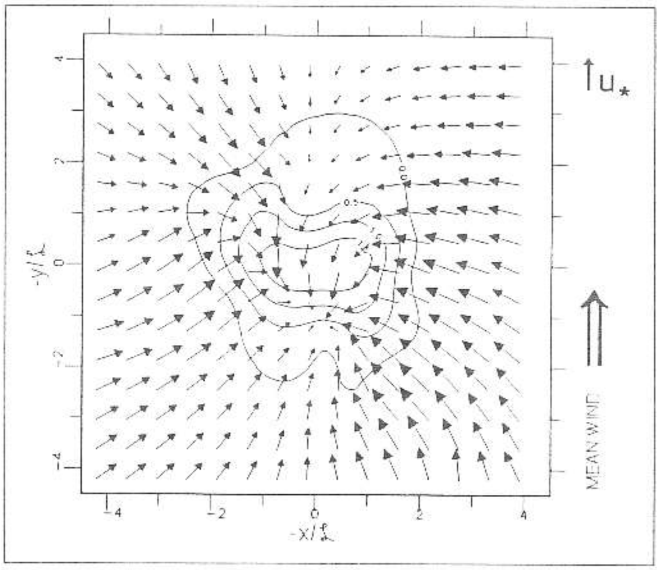

FIGURE 3. As Figure 2, but for $-z / L = 0.9 - 1.6$.

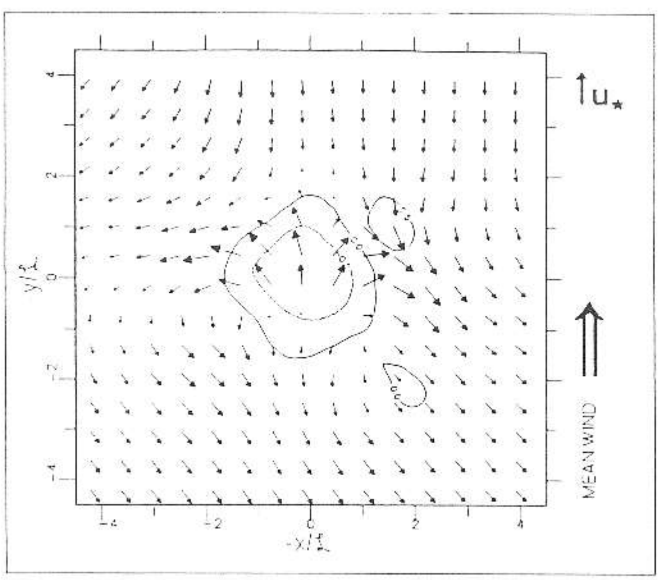

FIGURE 4. Horizontal cross-section for "cool down" structure in the surface layer at $-z / L = 0.2 - 0.7$. Mean wind direction is up the page. Contours are w/u.

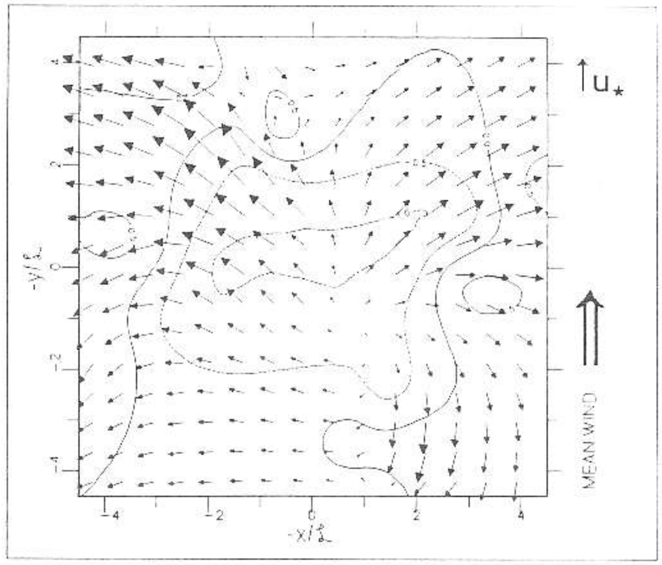

FIGURE 5. As Figure 4, but for $-z / L = 0.9 - 1.6$.

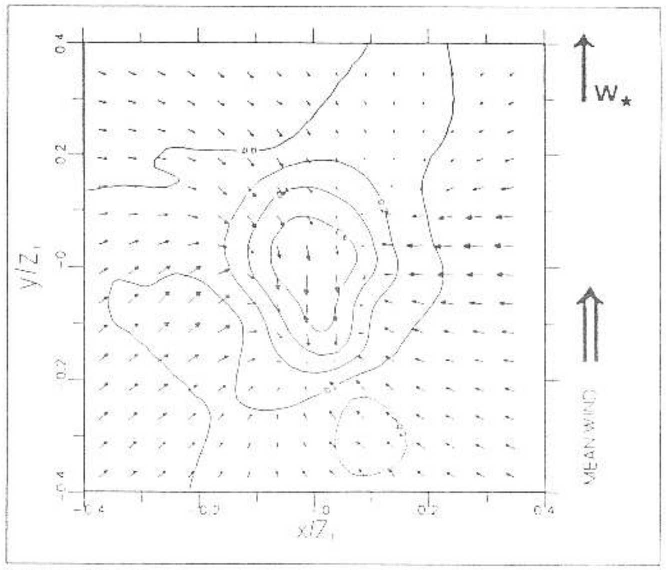

FIGURE 6. Horizontal cross-section of "warm up" structure in the ML for the height range $0.15 < z / Z_i \leq 0.20$. Arrows are horizontal wind deviations, scaled with w_*. Contours are w / w_*.

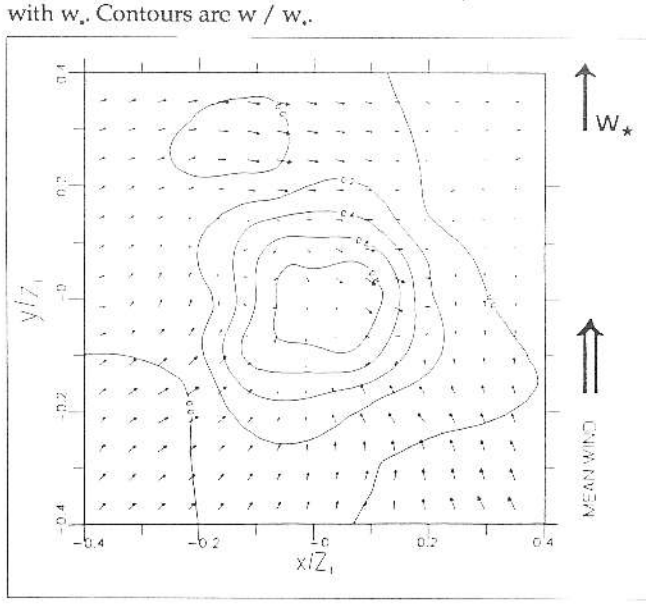

FIGURE 7. As Figure 6, but for $0.3 , z / Z_i \leq 0.5$.

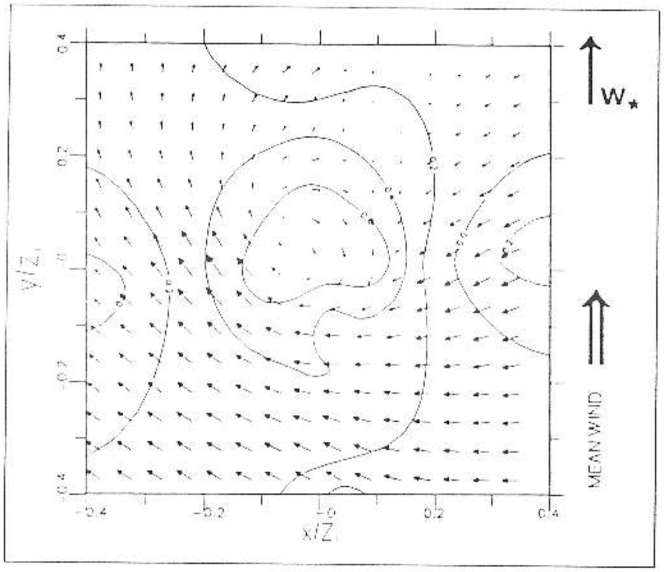

FIGURE 8. As Figure 6, but for $0.5 < z / Z_i \leq 0.6$.

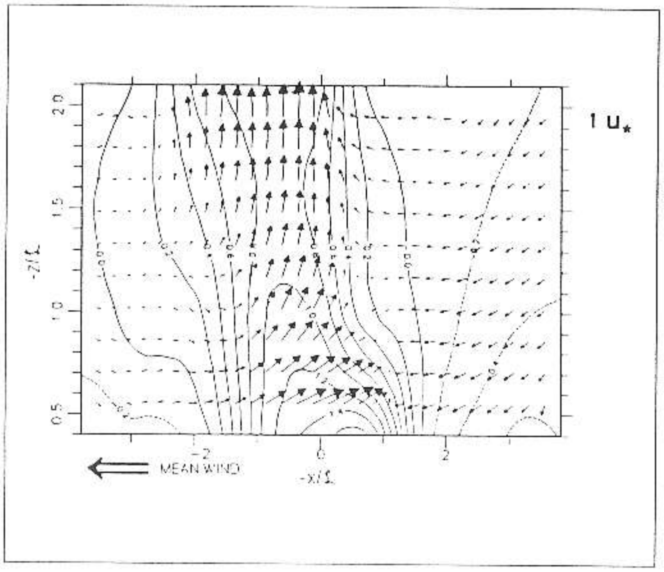

FIGURE 9. Vertical cross-section in the along-ind direction of "warm-up" structure in the SL. Arrows are wind deviations, scaled with u_*. Contours are θ / θ_{SL}.

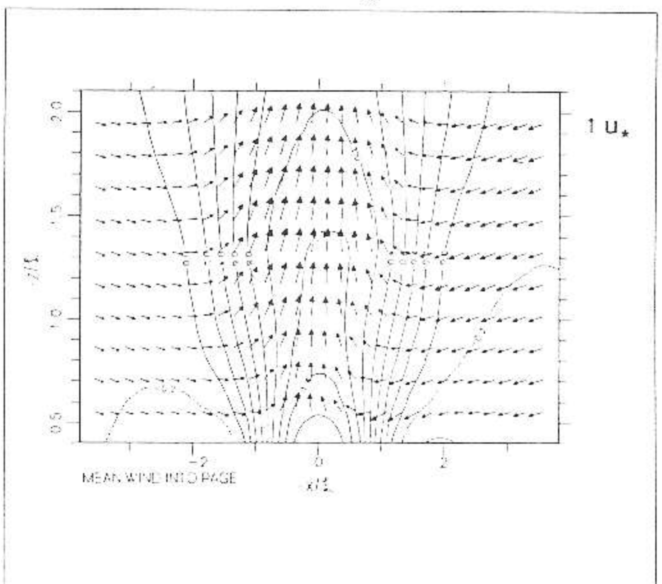

FIGURE 10. Vertical cross-section in the across-wind direction of "warm-up" structure in the SL. Arrows are wind deviations, scaled with u_*. Contours are θ / θ_{SL}.

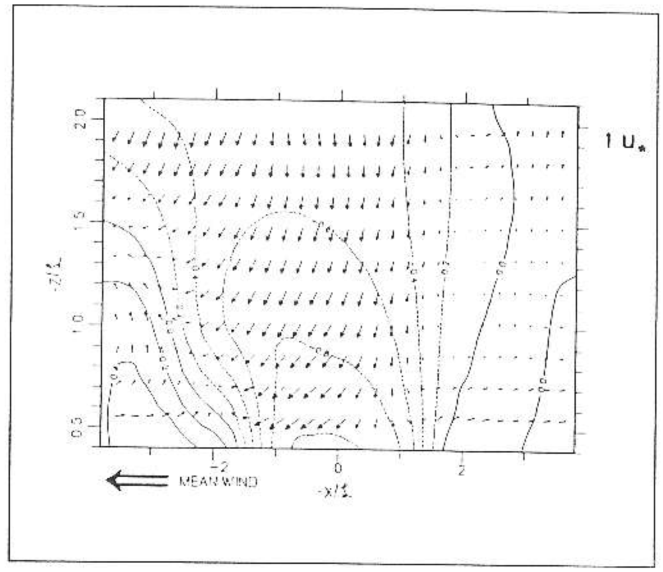

FIGURE 11. As Figure 9, but for "cool-down" structure.

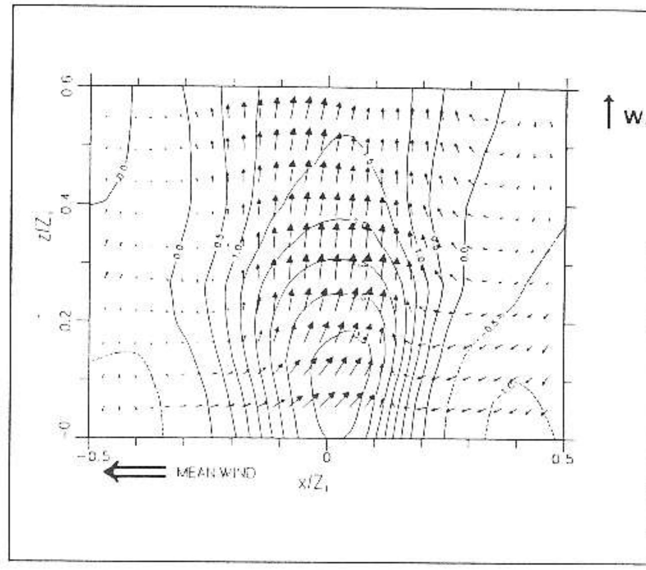

FIGURE 12. Mixed layer "warm-up" vertical cross-section in the along-wind direction. Arrows are wind deviations, scaled with w_*. Contours are θ / θ_*.

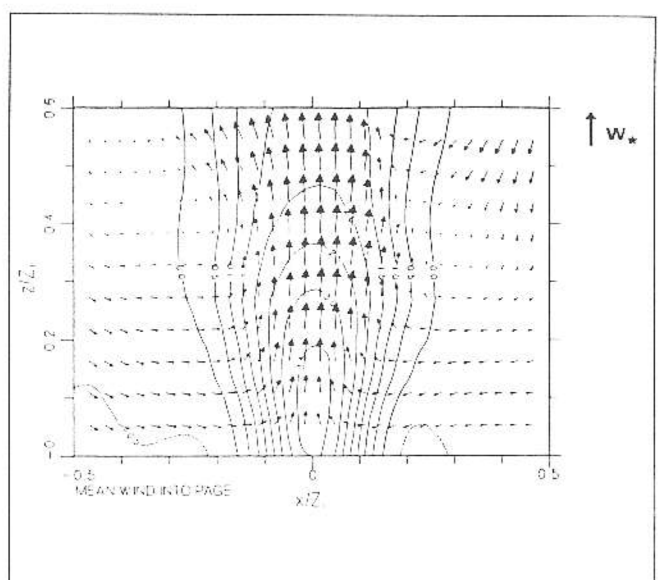

FIGURE 13. As Figure 12, but in the across-wind direction.

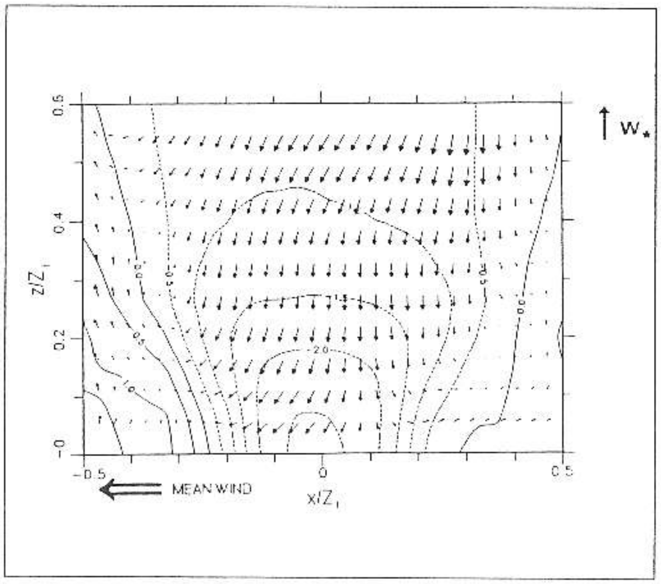

FIGURE 14. As Figure 12, but for "cool-down" event.

wind direction.

Figures 6, 7 and 8 show cross-sections through mixed layer thermals. Comparison of scales between Figures 2/3 and Figures 7/8 reveals that thermals are much larger structures than plumes. Since many SL plumes extend into the mixed layer, the data from which Figure 6 was constructed comprise a mixture of both types of phenomena. The results are thus intermediate between the two, and do not correctly represent either case. It should be stressed that this does not indicate that thermals and plumes coincide one-for-one in this region: the reality is somewhat more complicated (see Section 5).

For thermals in the middle of the mixed layer (Figure 7) the predominant motion is simply an upwards one. The cross-section formed from runs flown above $0.5Z_i$ (Figure 8), however, clearly shows a slow clock-wise rotation of the central thermal updraft and its environment, implying an upward spiraling motion. This does not imply, however, that all thermals are rotating: only the "average" case and possibly only in our particular study. Thermals are vastly variable phenomena, and the specific activity of a particular thermal is likely to be dependent upon many factors. These include its own recent history, its position with respect to adjacent thermals, horizontal changes in the wind direction profile through the CBL, and, under highly non-uniform surface conditions, the existence of "hot spots" on the ground and changes in topography. It is probably that the result shown here is produced by averaging together many non-rotating thermals with a small number of strongly rotating thermals.

4. Vertical Cross-Sections

Vertical cross-sections of composite structures in directions along and across the wind are shown in Figures 9 to 14. The contours shown are of (scaled) potential temperature deviations, and, therefore, represent the difference between the actual temperature at a given location, and the average temperature of all the air at that level (n.b. this is not the same as the average potential temperature in the CBL).

Figures 9 and 10 show views of a surface layer plume in the two orthogonal directions. The along-wind case (Figure 9) is the picture that would be seen by a surface layer tower arrangement, and compares well with composite cross-sections presented by Wilczak and Businger (1984) in a tower study in Colorado. The microfrontal convergence is clearly visible at the right side of the plume low down and the air feeding into it from upwind clearly dips downwards before entering. In contrast, the downwind inflow into the plume has a vertical velocity very close to zero. In the frontal zone, the temperature contours are more closely spaced than on the downwind side. In the across-wind direction (Figure 10), the plume is clearly thinner at the base and expands with height, whereas in the along-wind direction the opposite was true. A smooth, symmetrical inflow is evident from both sides of the plume, which clearly dips to downward velocities prior to entering it in the lower levels.

The "cool down" along-wind vertical cross-section (Figure 11) formed from data segments representing the environmental regions between plumes, complements fairly well that of the plume (Figure 9). The downdraft region is clearly broader and slower moving than the plume updraft. Towards the bottom, most of the divergent outflow is downwind and a convergence zone is evident around $-z/L = -2$, which probably marks the edge of the adjacent plume. Upwind of the downwards flow, there is little motion: the air is almost completely undisturbed, and the temperature deviation is uniformly zero.

The mixed layer "warm up" vertical cross-sections are given in Figures 12 and 13. In the region below about $0.2Z_i$ spurious influences from surface layer plumes effect the result, as discussed in Section 3. Again, it should be pointed out that the inference of a one-for-one linking between the structures in the surface layer and those in the mixed layer would be incorrect. In the center of the thermals, a pattern of uniform upwards motion is evident in both cross-sections, and there is also an indication of slightly divergent flow in the central core of the thermal. At the highest levels, in the region where the slow rotation appears in the horizontal cross-sections, upward flow is evident over an area wider than the central thermal core. The "cool down" picture (Figure 14) shows a slow, uniform downdraft, covering a region which is markedly larger than that occupied by thermals.

5. Summary and Discussion

The results discussed above are summarized in Figure 15, which shows a schematic depiction of processes in both the surface and the mixed layers and, in particular, the complex interactions in the transitional layer (TL) between these two layers. The diagram will now be used to explain in a simplistic way the basic processes of interaction between the structures of the two layers.

The convective eddies of the mixed layer take the form of randomly placed thermal towers (thick circles in Figure 15), each surrounded by a returning downward flow. These downflow regions interact with one another and range in shape and strength according to the distance between neighboring towers. The obstruction encountered by them at the surface forces divergent horizontal flow away from their bases. Strips of convergence subsequently form between competing downflow regions, along the lines joining close-neighbor thermal towers. These convergence lines form rough polygonal patterns in the surface layer, and are known as "thermal walls" (Webb 1977); Williams, 1991). Between the surface and the mixed layers thus exists a region of enhanced horizontal mixing, in which the structures of the two layers interact strongly. Surface layer plumes are pulled into groups from above by the action of thermal walls, causing stretching and distortion. At the center of each such group is one large

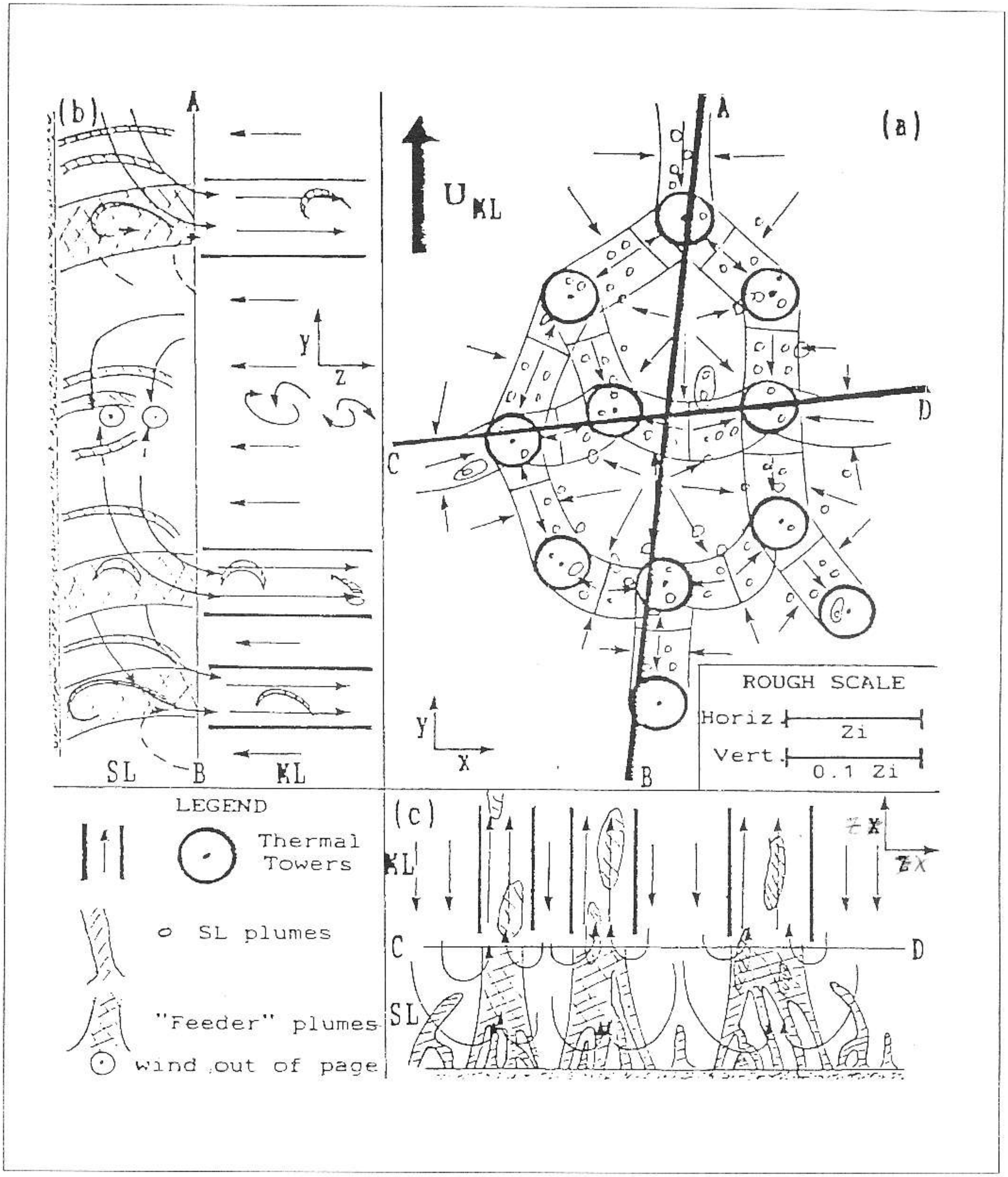

FIGURE 15. A diagrammatic depiction of the processes of interaction between the surface and mixed layers. (a) "Typical" horizontal cross-section through several ML-scale structures in the TL, showing flow patterns and the location of thermal walls; (b) Vertical cross-section along the down-wind line A - B; (c) Vertical cross-section along the across-wind line C - D. Note that the horizontal scale is greatly contracted compared to the vertical, and that the arrows are not to scale.

plume, which acts as a "central collector" (Williams, 1991). It is probable that this "central" plume is located in the convergence zone below a mixed layer thermal tower, and thus acts as a "feeding" mechanism. Adjacent surface layer air, including plumes and their environment, are caught in its enhanced inflow and move towards it and then up.

The processes depicted in Figure 15 are typical for a day with light to moderate winds. Stronger wind and especially wind shear within the mixed layer often leads to a much more pronounced organization of the convective elements into streets.

It is planned to use the aircraft and the processing algorithms to study the fine-structure of individual thermals in more detail in the future and to compare them with the more generalized composites presented above.

ACKNOWLEDGMENT

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REFERENCES

Antonia, R.A., Chambers, A.J., Friehe, C.A. and Van Atta, C.W., 1979: Temperatures Ramps in the ASL. J. Atmos. Sci., 36, 99-108.

Hacker, J.M. and Schwerdtfeger, P., 1988: The FIAMS Research Aircraft System Description, 2nd Edition. Flinders Institute for Atmospheric and Marine Sciences; Flinders University of South Australia.

Kaimal, J.C., 1974: Translation Speed of Convective Plumes in the ASL. Quart. J.R. Met. Sco., 100, 46-52.

Kaimal, J.C., and Businger, J.A., 1970: Case Studies of a Convective Plume and a Dust Devil. J. Appl. Met., 9, 612-620.

Schmidt, H. and Schumann, U., 1989: Coherent Structures of the Convective Boundary Layer Derived from Large Eddy Simulations. J. Fluid Mech., 200, 511-562.

Telford, J.W., 1986: Comment on "Large-scale Eddies in the Unstably Stratified Atmospheric Surface Layer," by Wilczak and Businer (1984), J. Atmos. Sci., 43, 499-500.

Webb, E.K., 1977: Convection Mechanisms of Atmospheric Heat Transfer from Surface to Global Scales. Second Australian Conference on Heat and Mass Transfer; The University of Sydney, 523-539.

Wilczak, J.M. and Businer, J.A., 1984: Large Scale Eddies in the Unstably Stratified Atmospheric Surface Layer. Part 1 (Wilczak): Velocity and Temperature Structure. Part 2 (Wilczak and Businer): Turbulent Pressure Fluctuations and the Budgets of Heat Flux, Stress and T.K.E. J. Atmos. Sci., 41, 3537-3567.

Wilczak, J.M. and Tillman, J.E., 1980: The Three-Dimensional Structure of Convection in the Atmospheric Surface Layer. J. Atmos. Sci., 37, 2424-2443.

Williams, A.G., 1991: Internal Structure and Interactions of Coherent Eddies in the Lower Convective Boundary Layer. Ph.D. Thesis. Flinders University of South Australia.