NOTES AND CORRESPONDENCE

On Calculating the Buoyancy of Cores in a Convective Boundary Layer

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ABSTRACT

Aircraft measurements of vertical air motions are used in a process of conditional sampling to select updraft and downdraft cores during a period of strong lake-effect convection. Corresponding measurements of temperature and moisture are used to calculate the buoyancies of the cores and to evaluate the dependence of the calculated buoyancy on the horizontal extent of core environment used in the calculations. Results suggest that calculated buoyancies are relatively insensitive to the definition of core environment.

1. Introduction

Convective boundary layers (CBL) often exhibit local areas of relatively strong upward or downward air motions (cores) driven, at least in part, by buoyancy. The buoyancy of an air parcel is related to the difference between its virtual temperature and that of its environment, with due consideration for any liquid or solid water that may be present. This note explores how calculated values of buoyancy of cores in a convective boundary layer may depend upon what one considers to be the core environment. Conditional sampling of aircraft data obtained during a period of strong lake effect convection is used to identify updraft and downdraft cores. Buoyancy values are calculated for each core, using several different distances to represent the core environment. Thus, this paper provides an observational check on the sensitivity of calculated core buoyancy to the lateral distance used to define the environment.

2. Background

Data used in this study came from the University of Chicago lake snow project. On 21 January 1984, an Arctic air mass centered over Kentucky brought cold, dry, southwesterly winds across Lake Michigan. Air crossing the upwind shore of the lake was very stable with a surface air temperature of −29°C. The lake surface temperature was between 0° and +1°C. Lake-effect convection was vigorous. The NCAR King Air (N312D) flew a vertical stack of passes at 14 levels positioned almost directly downwind from an upstream raob (in both space and time), 160 km from the upwind shore and about 20 km from the downwind shore. Pass heights ranged from well within the surface layer to well above all evidence of cloud and CBL activity.

Several pass-average statistics are given in Table 1. It is seen that the CBL extends to about 866 m, above which theta increases at a rate of over 11 K per km, in agreement with the upwind sounding. The top of the CBL was taken as 1000 m, at which level about 50% of the pass was in air having evidence of involvement with the boundary layer (based on the presence of cloud particles and/or moisture greater than that found above the CBL). The presence of cloud is taken as PMS FSSP concentrations $> 10\ \text{cm}^{-3}$; snow as PMS 200 Y concentrations $> 10\ \text{m}^{-3}$. The cloud layer, with a base at about 459 m and top at 1143 m, straddled the base of the inversion. The frequency of snow increased downward from the level of the highest overshooting turrets (about 1143 m) to a maximum of about 90% on passes below 594 m. The fraction of path lengths having upward air motions (up air) decreased upward from 50% at 20 m to 38% at 594 m, then increased to 50% above about 1140 m. A general discussion of the lake-effect convection on this date can be found in Braham (1986) and Braham and Kristovich (1994).

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TABLE 1. Pass statistics, flight of 21 January 1984.

Pass					Fraction of Pass		
Ht. m	Length km	Pres. mb	Temp. C	Theta K	Cloudy	Snowy	Up air
1323	4.2	843.9	−21.7	264.0	0	0	.50
1268	10.1	850.1	−21.8	263.3	0	0	.50
1143	30.0	865.4	−22.7	261.0	.05	.02	.50
1139	18.9	865.6	−23.1	260.6	.08	.03	.45
1069	23.6	873.6	−22.4	260.7	.03	.02	.45
1003	18.8	881.6	−22.6	259.8	.21	.12	.49
866	20.8	898.6	−22.3	258.6	.78	.38	.48
735	17.3	914.9	−21.3	258.3	.76	.62	.43
594	22.8	932.0	−20.0	258.3	.56	.86	.38
459	17.4	949.2	−18.7	258.3	.14	.86	.41
320	26.8	967.2	−17.3	258.3	0	.89	.41
188	19.6	984.4	−15.9	258.4	0	.96	.44
47	17.6	1002.4	−14.4	258.6	0	.90	.46
20	6.8	1006.1	−13.9	258.9	0	.90	.50
Lake		1009[a]	0.5[a]	273.7			

[a] Estimated.

3. Conditional sampling criteria

For each pass, measured vertical velocities were adjusted to give a pass-mean value of zero. Cores were defined as segments of flight track, two or more seconds long (roughly 150 m), having upward (downward) speeds greater than the mean of all upward (downward) speeds *for that pass*. Isolated interior seconds were allowed to drop below these values but not to change sign. Cores of like sign had to be separated by a minimum of 2 s of flight track; cores of opposite sign required no such separation. Cores thusly selected have the property of accounting for at least half the vertical mass flux at every level. Application of these criteria to the aircraft data resulted in the selection of 121 up-cores and 149 down-cores.

Several important characteristics of these cores are given in Table 2. To improve sample sizes, and in recognition of the fact that the passes at 1238 and 1323 m sampled similar conditions above the CBL and that passes at 1139 and 1143 m sampled similar conditions near the top of the CBL, data from these passes have been combined and are shown at 1296 m and 1141 m, respectively. The number (N) of up- and down-cores at each level are given, as well as the number of cores that showed indications of having involved boundary layer air (N CBL). Threshold values of vertical velocity used to define cores are given in column 4. Cores account for roughly 60%–70% of the up- and down-air mass fluxes though they cover only about 30%–45% of the up- and down-air pass lengths, except at the two lowest levels where their contribution to both the pass lengths and mass fluxes are substantially less. At these levels, the flux carried by cores is only 30%–50% because a greater fraction of the convective eddies are less than 150 m in diameter, and therefore not selected as cores.

4. Core sizes and speeds

Table 2 gives the median and 75th percentile values of core sizes at the different levels. The measured sizes of cores ranged from about 150 m (prescribed by the core criteria) to over 1700 m. There seems to be a slight tendency for up-cores to increase in size up through about 735 m and decrease in size above that height. No clear trend is seen for the down-cores. Not shown in Table 2 is the fact that the number of cores > 500 m in diameter is substantially larger in the downdraft group. The values of cores sizes given in Table 2 are somewhat less than the true sizes because aircraft penetrations would be expected to only rarely traverse the widest parts of the cores.

Core-average speeds for the updraft group increased from about 0.7 m s^{-1} at 20 m to about 2 m s^{-1} at 320 m, above which it decreased slowly to the base of the capping inversion. The mean speeds of down-cores was roughly constant at about 1 m s^{-1} from the base of the inversion down to 188 m, then decreased to the lowest level of measurement. One-second-average vertical velocities (not shown) increased upward to peak values over 4 m s^{-1} at 584 and 735 m in up-cores and increased downward to over 2 m s^{-1} at 459, 320, and 188 m in down-cores.

5. Core buoyancies

In this study, core buoyancy is taken as the difference between core-mean and environment-mean virtual temperatures, disregarding any effect due to solid and liquid water, which is much smaller than the effect due to vapor in these cases. In a CBL where the virtual temperature varies both inside and outside the core, values computed for buoyancy depend upon how one defines the environment. In the report by Braham and

Kristovich (1994), the environment of each core was taken to be the distance traveled by the airplane in 5 s, about 375 m, on either side of the core. The choice of 5 s of airplane travel to represent the environment of each core was somewhat arbitrary, although it reflected the facts that the nearby environment would be more important than the distant environment, and that a distance of 375 m is roughly equal to the average size of the cores as measured along the aircraft track. Moreover, the combined width of the core and 375 m on either side of it is about equal to the boundary layer depth, which should give an approximate scale for thermal influence on convection.

Since data are available for the entire length of each pass, we have now calculated core buoyancies using varying distances as the "core environment" to examine how the calculated values change with different definitions of core environment. We have calculated buoyancy using 2, 4, 5, 10, and 15 s of flight path on either side of each core, plus the entire pass length, as the core environments. The results are given in Table 3 where elapsed seconds have been converted to distance using an approximate average true airspeed for the plane. The results are also given in Fig. 1, which shows the maximum, minimum, and median values of the calculated virtual temperature differences for each pass as a group of horizontal bars with different bars corresponding to different values of the horizontal distance used for the core environment. The length of flight track used to define the environment increases downward in each group, from 2-s at the top to entire pass length at the bottom.

6. Discussion

Referring to Figs. 1a and 1b, the differences between cores above and below 866 m (base of the inversion) immediately stand out. Core characteristics below 866 m are consistent with a simple model of convective overturning with warm updrafts and cold downdrafts. Above 866 m, values of core buoyancy are much larger, more variable, and show little systematic difference between up- and down-cores, perhaps because gravity waves were contributing to the observed vertical motions above the inversion level.

The median values calculated for each definition of core environment, at every pass height, are probably the most meaningful statistic to consider in generalizing these results. As expected, below 866 m the up-cores were positively buoyant with maximum values at lowest levels. Down-cores are colder than their environment below 459 m with maximum differences at the lowest levels. At 1296 m, above all evidence of CBL involvement, the up-cores tend to be cold and down-cores warm. Perhaps these are dynamically induced clear air motions above, and between, the overshooting turrets. In the upper parts of the cloud layer and above the base of the capping inversion, median values of

TABLE 2. Characteristics of convection cores, 21 January 1984.

	Updraft cores								Downdraft cores							
				Core size			Contribution to					Core size			Contribution to	
Pass ht m	N	N CBL	Threshold (m s^{-1})	med (m)	75th (m)	Mean speed (m s^{-1})	path[a] (pct)	flux[b] (pct)	N	N CBL	Threshold (m s^{-1})	mean (m)	75th (m)	Mean speed (m s^{-1})	path[c] (pct)	flux[d] (pct)
1296	17	0	0.3037	375	525	0.46	48	78	11	0	0.3109	525	712	−0.53	37	71
1141	15	2	0.4480	300	450	0.74	37	70	15	5	0.3957	300	450	−0.65	43	68
1069	9	0	0.4348	443	630	0.75	37	68	13	1	0.3510	236	788	−0.57	40	68
1003	9	5	0.4449	315	472	0.78	34	56	9	7	0.4302	315	433	−0.80	37	65
866	12	10	0.6019	232	309	1.13	34	59	14	13	0.5590	232	464	−0.90	41	65
735	4	4	0.8000	544	870	1.72	31	68	13	13	0.6015	290	363	−1.01	41	70
594	7	7	0.9860	362	760	1.75	33	70	13	13	0.6037	398	507	−0.92	44	68
459	8	8	0.9920	290	436	1.66	39	72	11	11	0.6846	363	545	−1.16	39	65
320	13	13	1.0670	224	448	2.10	34	68	16	16	0.7280	299	821	−1.11	47	68
188	13	13	1.0370	253	326	1.91	38	71	14	14	0.7998	362	434	−1.25	43	65
47	11	11	0.6591	221	332	1.02	36	52	16	16	0.5578	221	295	−0.82	43	56
20	3	3	0.4646	225	263	0.70	22	31	4	4	0.4749	225	225	−0.76	27	43

[a] Percent of up-air pathlength contained in up cores.
[b] Percent of up-air mass flux contained in up cores.
[c] Percent of down-air pathlength contained in down cores.
[d] Percent of down-air mass flux contained in down cores.

TABLE 3. Median differences between core-average virtual temperatures and environment-average virtual temperatures, as a function of environmental distances, for various pass heights.

Height above lake—(m)	Updraft cores Environmental distance—(km)						Downdraft cores Environmental distance—(km)					
	0.150	.300	.375	.750	1.125	Pass	0.150	.300	.375	.750	1.125	Pass
1296	0.01	−0.03	−0.03	−0.05	−0.09	−0.11	0.04	−0.01	−0.01	0.03	0.03	−0.08
1141	0.02	0.08	0.11	0.08	0.18	0.09	0.16	0.07	0.06	0.10	0.04	0.18
1069	0.12	0.20	0.19	0.14	0.16	0.25	−0.02	−0.02	0.15	0.19	0.16	0.06
1003	−0.02	0.03	0.07	0.05	0.10	−0.34	0.21	0.48	0.23	0.56	0.28	0.32
866	0.03	0.04	0.01	0.02	0.01	0.02	−0.01	−0.02	−0.03	0.02	−0.02	0.01
735	0.03	0.03	0.04	0.02	0.03	0.08	−0.01	−0.02	0.01	0.01	0.00	0.01
594	0.04	0.06	0.05	0.06	0.06	0.10	−0.03	−0.01	−0.01	0.00	0.02	0.01
459	0.07	0.08	0.08	0.08	0.07	0.08	−0.01	−0.02	−0.02	−0.02	−0.01	−0.02
320	0.10	0.14	0.16	0.11	0.10	0.16	−0.01	−0.06	−0.07	−0.04	−0.05	−0.05
188	0.18	0.13	0.13	0.19	0.16	0.16	−0.10	−0.09	−0.12	−0.13	−0.09	−0.05
47	0.24	0.24	0.26	0.26	0.22	0.22	−0.20	−0.18	−0.16	−0.14	−0.18	−0.23
20	0.33	0.22	0.24	0.30	0.32	0.36	−0.28	−0.22	−0.20	−0.26	−0.27	−0.30

buoyancy are generally warmer than the environment, for both up- and down-cores. The reasons for this are not yet fully sorted out.

Very generally, we find that changing the definition of core environment changed calculated buoyancy values only by about 10% of the mean. Change of buoyancies with height above the lake was a much larger factor. Only for a few of the down-cores, at midlevels where the core buoyancies were close to zero, did the calculated values change sign as different distances were used to define the core environment. There is a slight suggestion that calculated buoyancies may increase in magnitude with increasing length of environment used in the calculations. This may be a vagary of small sample sizes, but also it may indicate that the core selection criteria tended to select the inner, most buoyant, part of many convective elements.

Considering only the cores at 866 m and below—that is, in the most convective part of the CBL—these data suggest that calculated values of buoyancies of cores, *selected as they were in this study*, are rather insensitive to the amount of the core environment used in the calculation. This indicates that the conditional sampling criteria used for selecting the cores effectively identified entities that were thermally different than their background. Core selection criteria used in this study should be applicable to any well-stirred convective boundary layer heated from below and sampled over several wavelengths of the predominate convection. It may not be the most appropriate for cases of deep convection, but as yet, this has not been explored.

In many previous studies (e.g., Lucas et al. 1994) cores were defined in terms of a single vertical velocity threshold at all heights. In a turbulent convective boundary layer where peak 1-s up or down vertical velocities are only two or three times the pass average, and where pass-averages change by a factor of 2 to 4 in going from the subcloud to midlevel to the cloud top, it is difficult to select a single value for the core threshold that works equally well at all levels. Our desire was to select convective entities that had a reasonable chance of traversing the entire depth of the boundary layer. We have chosen to base the threshold on the average vertical velocity (up or down) at each level, in preference to a single arbitrarily selected value, because it is based upon the observed vertical velocity fields, and is connected to total mass overturning in a clearly defined way. Moreover, this technique is more in line with the physics of buoyancy-driven cores. For example, updrafts have small vertical velocities in the surface layer, accelerate upward to midlevels, and then decelerate in the outflow layer at the top.

Given the facts that all models of buoyant convection make assumptions about environmental sizes, and that little work has been done in this area, more numerical and observational work is needed to verify the representativeness of these results. More work

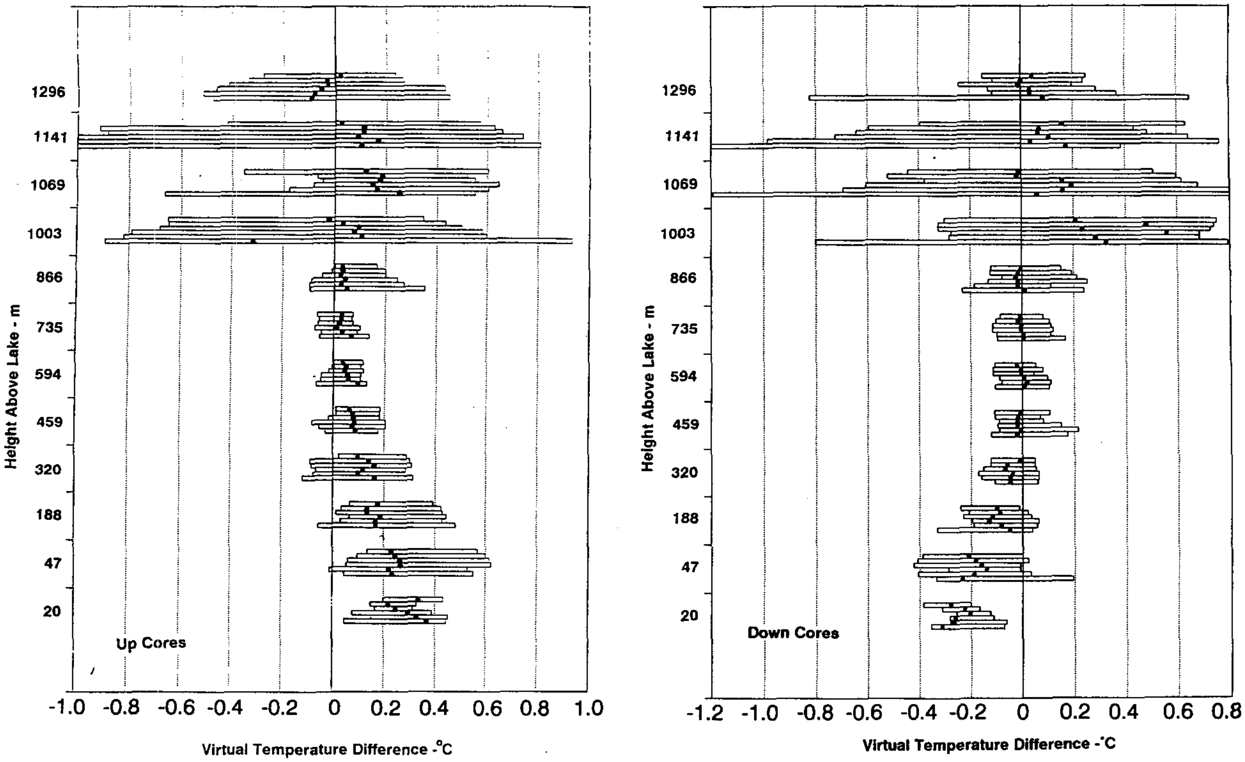

FIG. 1. Differences between core-average virtual temperatures and environment-average virtual temperatures for (a, left) up-cores and (b, right) down-cores, as a function of height above the lake surface. The group of horizontal bars at each height correspond to various lengths of environment used in the calculations, increasing from 150 m for the top bar to entire pass length for the bottom bar. Outer limits of each bar represent the overall range of calculated values; the closed circle within each bar gives the median value for that set of calculations.

should also be done to examine how the size effects on buoyancy are altered by the presence of mesoscale circulations.

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