

Transfer of Sensible Heat from the Ground and Development of the Convective Layer

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1. Introduction

The significance for thermal soaring of the depth of the ground-based convective layer is well known. Lindsay and Lacy (1976) report the experiences of many soaring pilots showing that both strengths and heights of thermals increase with increase of convective-layer depth. Wallington (1977, p. 182) suggests the "... the best single indicator of the average strength of thermals is the depth of the thermal layer." The thermal layer, the convective layer, or as often called in meteorology and in air pollution work, the well-mixed (or simply "mixed") layer is the air layer formed primarily by turbulent transfer of sensible heat from ground to air. Buoyancy effects enhance the turbulence caused by the normal increase of wind speed with height. The mixing and consequent upward transfer of sensible heat result in the significant fact that a uniform height distribution of average temperature is established, viz., the dry-adiabatic lapse rate, a temperature fall of 0.98 deg C per 100 meters height. The top of the convective layer is usually considered to be the height at which the temperature begins to decrease at a smaller rate, or where the potential temperature begins to increase with height.

As sensible heat flux from the ground to the air increases in the morning hours after sunrise, the convective layer increases in depth. If other processes do not interfere, it continues to increase as long as the ground can supply heat. Ground-to-air heat transfer and convective layer growth are central to weather forecasting for thermal soaring.

Nearly a third of the OSTIV "Handbook of Meteorological Forecasting for Soaring Flight" is devoted to forecasting thermal convection. It includes a detailed procedure to forecast the hourly increase of the convective-layer depth from an early morning sounding and either forecast temperatures or estimates of the hourly rates of sensible heat transfer from the ground. The latter is often referred to as "solar heating" in the OSTIV Handbook as well as in other published works. It should be emphasized that only a part of the solar energy arriving at the ground at any one time is available for developing the convective layer. Ground reflection, evaporation, and soil warming may consume a significant portion of it. The second important influencing the rate of daytime growth of the convective layer at a given location is the net horizontal transport (advection) of heat. Other processes such as radiative absorption or

loss within the layer and creation and dissipation of turbulent energy are thought to be relatively insignificant.

One's ability to forecast the rate of sensible heat transfer from the ground to the air ultimately should be improved because of the recent work of Webb (1982). His intensive analysis of wind and temperature height distributions in the first few meters above the ground, during periods of heat transfer upward, make it possible to calculate sensible heat flux from suitable accurate wind and temperature measurements.

Webb's results were applied to data obtained in the Great Plains Turbulent Field Program at O'Neill, Nebraska, U.S.A. in August and September, 1953, published by Lettau and Davidson, (1957, Vols. 1 & 2)* and by Thornthwaite et al. (1953).

The calculations are in three groups: (a) Determination of the hourly sensible heat fluxes from ground to air, for each daytime hour of seven observation days of the O'Neill experiments, with equations developed by Webb (1982); (b) Determination of the heat advection for the convective layer for each of the seven days for the period 0830 to 1030 CST by means of the published geostrophic winds and the thermal wind equation, and (c) Calculation of the depth of the convective layer at 1030 CST that would result from the heat sums from (a) and (b) for the two-hour period. The resulting depths are shown on each of the 1030 CST graphs of temperature soundings (marked by arrows on Figure 3) to judge, for these periods, the validity of the calculation schemes as well as the applicability of such information to forecasting convective depths. The specific calculations undertaken were prescribed primarily by the nature of the available measurements.

2. Sensible Heat Flux from Ground to Air

Webb's analysis yields the following equation for sensible heat flux:

$$Q_w = \rho c_p k_u k_0 (U_b - U_a) (\theta_b - \theta_a) S_u^{-1} S_\theta^{-1} \quad (1)$$

in which ρ is density, c_p specific heat at constant pressure, k_u , k_0 von Karman constants for wind and temperature respectively, U_a , U_b average wind speeds at

heights a and b , θ_a , θ_b average potential temperatures at the same two heights and S_u and S_θ are functions of stability determinable through calculation of the Richardson number. Webb derived an S function for each of four stability ranges basing his analysis on similarity of wind and temperature vertical profiles in the atmospheric surface layer. By careful manipulation of unusually accurate data he was able to obtain results without the use of direct flux measurements. The data he used, in fact, included some of the wind and temperature data used in the present analysis. Others were from similar experiments in Australia (Swinbank and Dyer, 1968).

The wind and temperature data used in the present calculations were those obtained by the Johns Hopkins University group during the O'Neill experiments. The values of k_u and k_0 were assumed identical and equal to 0.41.

The daily sums of Q_w for all hours during which the sensible heat flux was directed upward from the ground are listed in Table 1, together with daily sums of hourly values, for the same hours, of net radiation exchange at the surface, R , and the net heat flux into the soil, G . The net radiation exchange was measured directly with an aspirated radiometer and the soil heat flux data were determined by Portman (1955) from soil temperature, moisture, density and direct flux measurements.

Table 1. Heat flux and soil moisture data for O'Neill observation days, sunrise to sunset.

Period	Q_w	R	G	S.M.
1 9 Aug	122	394	44	9.0
2 13 Aug	117	404	62	7.8
3 19 Aug	98	361	46	8.2
4 22 Aug	135	330	47	6.5
5 25 Aug	180	347	48	4.6
6 31 Aug	222	335	38	2.5
7 7 Sep	163	297	39	5.4

Q_w = sensible heat flux, cal/cm²

R = net radiation, cal/cm²

G = soil heat flux, cal/cm²

S.M. = soil moisture, percent

The sensible heat flux data for the seven days can be compared with heat fluxes derivable from data in Table 1, page 10 of the OSTIV Handbook. The latter are average air-layer thicknesses (in millibars) that can be changed from isothermal to adiabatic states, given for different

* Throughout the remainder of this paper these sources are designated as Vol. 1 or Vol. 2. Volume 1 contains descriptions of instruments and measurement methods, Volume 2, most of the experimental data.

months of the year, for each hour after sunrise. These were converted to heat flux values by the relationship

$$Q_o = \frac{c_p}{g} T_1 \left\{ p_o [(\kappa+1)^{-1} (p_o/p_1)^\kappa - 1] - p_1 [(\kappa+1)^{-1} - 1] \right\}$$

for which a derivation is given in an appendix. In this equation

Q_o = sensible heat

T_1 = temperature of the isothermal layer and the temperature at p_1

p_1 = pressure at the top of the layer

p_o = surface pressure

g = acceleration due to gravity

c_p = specific heat at constant pressure

$\kappa = R/c_p$

R = gas constant for dry air.

Calculated values, accumulated hour by hour after sunrise, for August and September, are shown in Figure 1 along with similar accumulated hourly values of the O'Neill days.

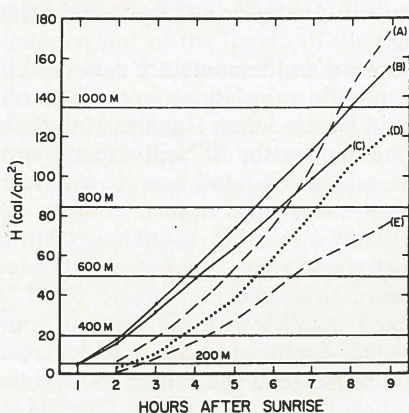


Fig. 1 Accumulated heat flux from the ground to the convective layer:

(A) The O'Neill day (31 Aug.) with the greatest heat flux

(B) August data from the OSTIV Handbook

(C) September data from the OSTIV Handbook

(D) Data averaged from the seven O'Neill days

(E) Data from the O'Neill day (19 Aug.) with the least flux.

Shown also is a scale of convective layer depths obtained with the aid of an equation due to Neiburger (1941), vis.,

$$Z = (2Q_o / \bar{\rho} c_p)^{1/2} \quad (3)$$

in which Z = depth of the convective layer
 Q_o = heat added to the layer to change it from isothermal to adiabatic

c_p = specific heat at constant pressure

$\bar{\rho}$ = mean density of the layer.

Following Neiburger, the mean density was taken to represent average summer conditions at 40° latitude in the United States and do not necessarily represent either the OSTIV curves or those from the O'Neill experiment.

As shown in Figure 1 the average sensible heat fluxes calculated for the seven O'Neill days (Curve C) are less than either

the September or the August data from the OSTIV Handbook. At two hours after sunrise there is a difference of about

15 cal/cm². It increases to 30 cal/cm² by 4 hours after sunrise and after six hours, i.e., about noon, the difference decreases to 20 cal/cm². The corresponding convective layer depth difference remains at about 200 meters from an hour after sunrise until noon in accordance with Equation 3. The O'Neill data for the day with the greatest sensible heat flux, 31 August, are also less than the OSTIV data until nearly seven hours after sunrise. By nine hours after sunrise, however, the maximum O'Neill data are 20 cal/cm² greater than the 155 cal/cm² indicated by the August OSTIV curve. At this height 20 cal/cm² corresponds to a difference of less than 100 meters. The O'Neill data for the day with the least heat flux, 19 August, are 50% less than the OSTIV August data by the ninth hour after sunrise, corresponding to a depth difference of nearly 300 meters.

The conditions for which the OSTIV data are valid, as described in the Handbook, can be summarized as follows:

- (a) A location at 50 degrees north latitude;
- (b) Flat and relatively low-lying ground, not unusually moist;
- (c) An albedo of about 25%; and
- (d) Mainly clear sky during at least the first part of the day.

Because the observations were taken at about 42.5 degrees north the calculated convective heat could be expected to be somewhat greater than that indicated by the OSTIV curves. Calculation of the extraterrestrial solar radiation, i.e., the amount received outside the atmosphere, for the dates of the observations shows that the greater amount received at O'Neill increased from about 5% on 9 August to about 13% on 7 September. Apparently this effect was offset by other factors.

Early morning measurements of soil moisture at a depth of 2.5 to 5 cm varied from about 9% (wet-weight basis) on 9 August to about 2.5% on 31 August. Precipitation recorded at O'Neill shortly before

and during the period is given in Table 2. The normal August precipitation is about 6.4 cm.

Table 2. Precipitation recorded at O'Neill, 1953.

25-30	July	8.5 cm
10	August	0.6 cm
11	August	0.2 cm
15	August	1.8 cm
2	September	0.1 cm
3	September	0.6 cm

Albedo measurements were made on 4, 5, 6, and 7 September. They were averaged for the four days for each hour of measurement and are given in Table 3. If the differences between these values and the 25% appropriate for the OSTIV data are applied to the solar radiation measurements on 31 August it is found that there was about 6 cal/cm² (about 3% of the total convective heat) more radiation reflected from the O'Neill surface for the nine hour period. During August when the soil moisture was greater and the grass greener, a lower value of albedo can be assumed. One may conclude that possible effects of higher albedos are counteracted by the effect of latitude in comparison to appropriate OSTIV conditions.

Cloud conditions for the seven observation periods reported in Vol. 2 are given in Table 4 for time intervals appropriate for the data in Figure 1, together with the measured total solar radiation for the entire day and its ratio to calculated extraterrestrial solar radiation. The solar constant was taken to be 1.965 cal/cm². The cloud on the three "cloudy" days must have been unusually thin and transparent, since the radiation ratios were within a few percentage points of the average for the four "clear" days.

A comparison of the two O'Neill days for which individual cumulative curves are given in Figure 1 shows that the reported clouds may indeed not have been significant in determining the amount of sensible heat flux from the ground to the convective layer. Data for the nine hour period after sunrise for each day are listed in Table 5. The striking fact is that although both insolation and net radiation sums for the cloudy day were greater than those for the clear day, the sensible heat flux on the cloudy day was less than half

Table 3. Average albedo measured at O'Neill, 4-7 September, 1953.

CST	0735	0835	0935	1035	1135	1235	1335	1434
Albedo, %	45	35	28	24	22	23	24	25

Table 4. O'Neill cloud observations, total recorded solar radiation (sunrise to sunset) and ratio of total solar to calculated extra-terrestrial solar radiation (sunrise to sunset).

CST Period	0630	0830	1030	1230	1430	Sol.	Sol./ex.
1 9 Aug.	4 AcCs	5 AcCs	9 AcCs	9 AcCs	7 AcCs	634	0.70
2 13 Aug.	Clear	Clear	Clear	Clear	Clear	678	0.77
3 19 Aug.	9 AcCs	9 AcCs	7 AcCs	7 AcCs	7 CuCs	624	0.73
4 22 Aug.	3 AcCs	1 Cs	9 AcCs	8 Cs	9 CuCs	600	0.71
5 25 Aug.	Clear	Clear	Clear	Clear	Clear	619	0.75
6 31 Aug.	1 ScAc	Clear	1 Ac	Clear	1 Cu	592	0.75
7 7 Sep.	1 Ci	1 Ac	Few AcCi	Few Cu	Few CuAc	570	0.76

Table 5. Heat flux sums for the nine-hour period following sunrise.

Cal/cm ²	Period 3 19 Aug. CLOUDY	Period 6 31. Aug. CLEAR
Total solar radiation	484*	468*
Net radiation exchange	297	278
Soil heat flux	44	33
Sensible heat flux	81	173

*Values for alternate hours were interpolated.

of that for the clear day. The explanation seems to be in the apparent difference in evaporation. The marked effect of soil moisture on sensible heat flux for the O'Neill observation periods is easily seen in Figure 2 in which values of the heat flux ratio $Q_w/(R-G)$ are plotted opposite the early morning measurements of soil moisture. Clearly the greatest day-to-day variation of sensible heat flux to the convective layer during the seven O'Neill experiments was due to soil moisture available for evaporation. Variations in other terms in the surface heat balance, along with cloudiness, were apparently much less significant.

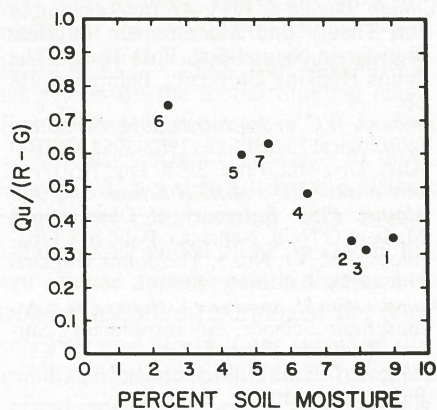


Fig. 2 Ratios of sensible heat flux to net radiation minus soil heat flux for the seven O'Neill days (sunrise to sunset) and early morning soil moisture.

3. Advection in the Convective Layers

Suitable wind data for calculating advection during the daytime hours of the O'Neill experiments were available for only 0900 CST each day. Temperature soundings, on the other hand, are published for every other hour on the half hour. With only this information readily available, it was decided to evaluate advection for each of the observation days for the two-hour period 0830 to 1030 CST. The computed advective fluxes were added to the computed sensible heat fluxes, Q_w , for the same two-hour periods. The sums were used with Equation 3 to determine convective-layer depths to be compared with those appearing on the 1030 CST soundings. The following equations were used for the advection calculations:

$$\Delta T = \frac{f}{R \ln(p_1/p_2)} (v_1 u_2 - v_2 u_1) \quad (4)$$

$$Q_{adv} = \left(\frac{c_p}{g}\right) \Delta T (p_0 - p_{c1}) \quad (5)$$

in which
 ΔT = mean temperature change in the layer

f = the Coriolis parameter

R = the gas constant for dry air

P = pressure

u = west component of the wind

v = south component of the wind

c_p and g are as defined before and the subscripts 1 and 2 refer to the lower and upper bounds of the layers for which data are reported. The subscript 0 refers to the surface and cl to the convective layer depth. Equation 4 follows directly from the thermal wind equation developed in many meteorology text books (e.g., Wallace and Hobbs, 1977). Equation 5 results from the substitution of the hydrostatic equation in the basic equation for temperature change from heat addition without pressure change. Because the convective depths themselves were partially determined by the results of Equations 4 and 5 it was necessary to use an iteration procedure to obtain the correct pressure differences for the calculations. The results are listed as two-hour amounts in cal/cm² in Table 6 along with the two-hour Q_w sums for each of the seven observation days.

Table 6. 0830 to 1030 CST convective (Q_w , cal/cm²) and advective (Q_{adv} , cal/cm²) heat fluxes with resultant convective layer depths (Z , m).

Period	Q_w	Q_{adv}	Z
1 9 Aug	36.2	7.5	590
2 13 Aug	23.4	-8.2	345
3 19 Aug	20.0	7.0	455
4 22 Aug	25.0	11.5	531
5 25 Aug	34.5	21.5	665
6 31 Aug	34.8	2.2	541
7 7 Sep	30.8	8.9	552

As can be seen, all but period 2 calculations produced positive amounts and they ranged from about 6% of the accompanying Q_w values (period 6) to about 60% (period 5). It is difficult to assess the reliability of these computations because of the many necessary assumptions. They

should be regarded as estimates based on the best information available, and at the same time, they represent the kind of information that one might use for early morning convective depth forecasting. Convective depths calculated from Equation 3 with the sum ($Q_w + Q_{adv}$) substituted for Q_0 are also listed in Table 5. The mean densities were calculated from the reported height distributions of temperature and humidity and the equation of state. It was necessary, again, to use an iteration procedure to establish the appropriate mean density values. The iteration calculations of Equation 3 were combined with those for the advection to achieve appropriate pressure differences and densities for the final convective depths.

The resulting convective depths are shown with the 1030 CST temperature soundings for all 7 periods in Figure 3. Except for the first two periods the sounding temperatures were derived from both radiosondes and L-20 aeroplane data that were interpolated and averaged as reported in Vol. 2. For the first two periods there were no aeroplane data.

Except for period 5, calculated convective depths are less than those indicated by lapse rate changes from the adiabatic at heights of 400, 600 or 800 m in each of the soundings. A better determination of convective depths from the sounding data for periods 4, 6, and 7, however, might be made by extrapolating the dry adiabatic lapse rate upward from the 400 m level and the data at 600 m, and above, downward linearly to the height at which the two extrapolations meet. Such extrapolations may be justified because of the original averaging to obtain temperatures at the standard heights. If this is done, depth differences for these three periods, along with that for period 2, are all about 50 m or less. At these heights 50 m corresponds to about 5 cal/cm², a value probably well within a precision that can

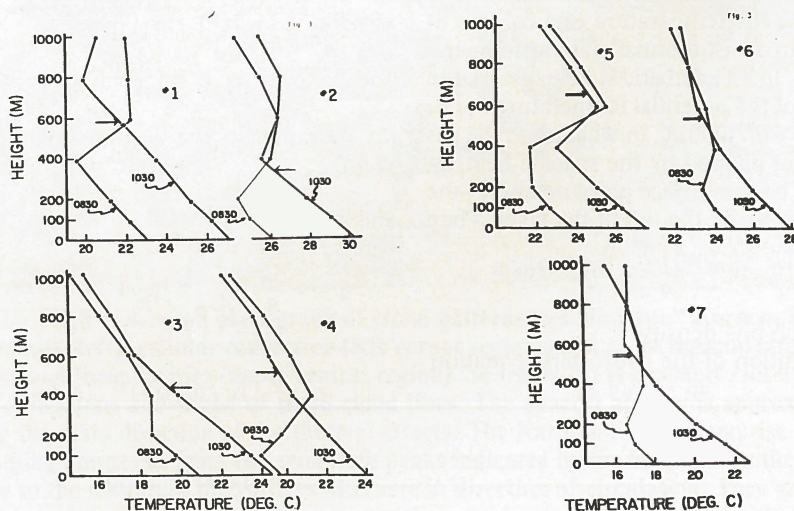


Fig. 3 Temperature soundings for the seven O'Neill periods with convective depths indicated on each 1030 CST sounding.

be expected from the heat flux calculations with the available data. Similar extrapolations of the adiabatic lapse rate upward for the other periods

would create apparently stronger inversions and, except for period 5, greater differences between calculated and observed convective depths. As they are shown, periods 1 and 3 had depth differences of about 200 and 150 m, corresponding to heat fluxes of 50 and 15 cal/cm², respectively, for the height intervals involved. It is likely these amounts of heat were transferred downward through the inversion layer. In period 1 the heat loss indicated by the temperature drop from 0830 to 1030 above 600 m is particularly indicative of this fact. The maximum wind speeds reported for this period, furthermore, in the vicinity of the version layer were 21.4 m/sec at 0830 and 19.4 m/sec at 1030. These were higher than comparable speeds for any other period. For period 5 the calculated convective depth appears to be more than 250 m greater than the height indicated by the sounding. The calculated advective heat for this period, 215 cal/cm², was about twice as large as the next nearest value. A review of the data suggests nothing to account for this anomaly. Except for the possibility of extrapolating the adiabatic lapse rate above the 400 m level and thereby increasing the apparent inversion strength, a supportable explanation for the large difference cannot be offered at this time.

4. Summary and Conclusions

1) Calculations of sensible heat transfer from the ground to air via relationships developed by Webb (1982) appear to provide reliable data in relation to other terms of the surface heat budget and to growth of the convective layer. The ratios

of the sensible heat flux to the net radiation diminished by the soil heat flux, $Q_w / (R-G)$ show a systematic decrease with increase in soil moisture. The latter has a greater influence on convective layer depths than differences in cloudiness.

2) The cumulative values of calculated sensible heat flux for the nine-hour period after sunrise, averaged for the seven observation days, are consistently lower than those derived from either September or October data in the OSTIV Handbook. Only the data after the seventh hour for the day with the greatest heat flux exceeded the OSTIV values. The day with the lowest heat flux, 19 August, had only about 50% of the amount indicated by the OSTIV data for the nine hour period.

3) Calculations of advective heat transfer for the morning hours 0830 CST to 1030 CST for each of the seven days yielded apparently reliable quantities for 6 of the 7 days.

4) Each of the convective depths derived from the calculated advective and convective heat fluxes for 4 of the 7 0830 to 1030 periods were within about 50 meters of those determined from the 1030 soundings.

Convective depths calculated for two other periods were less than those indicated by the soundings by about 150 m and 200 m. These differences in depth can be explained by heat transfer downward. The calculated convective depth for the remaining period was more than 250 m greater than that indicated by the sounding. The anomaly can be associated with the apparently too-large advective flux for this period but defects in the data could not be identified to support the conjecture.

5) Application of Webb's relationships to calculating sensible heat flux from the ground to the convective layer appears to be a reliable way to examine quantitatively the processes involved in the growth of convective layers when suitable data are available.

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APPENDIX

Derivation of Equation 2

Let Q be the amount of heat required to increase the temperature of a column of air from an isothermal state at temperature T_1 to an adiabatic state expressed in terms of the potential temperature θ , i.e., $T(P) = \theta(P/1000)K$, in which K is the gas constant divided by the specific heat, c_p . Let P_0 be the surface pressure and P_1 the pressure at Z_1 , the top of the layer. Then

$$Q = \int_0^{Z_1} \rho c_p dT(z) dz$$

in which ρ is density. Substitution of the hydrostatic equation $dp = -\rho g dz$

gives

$$Q = - \int_{P_0}^{P_1} \frac{c_p}{g} dT(P) dP$$

in which g is the acceleration due to gravity.

$$\text{Let } dT(P) = \Delta T(P) = T(P) - T_1$$

$$\text{and for } T(P) = \theta_1 \left(\frac{P}{1000} \right)^K$$

$$\text{and } \theta_1 = T_1 \left(\frac{1000}{P_1} \right)^K$$

(as indicated in the accompanying diagram)

and

$$\begin{aligned} Q &= - \frac{c_p}{g} T_1 \int_{P_0}^{P_1} \left[\left(\frac{P}{P_1} \right)^K - 1 \right] \\ &= \frac{c_p}{g} T_1 \left\{ P_0 [(\kappa+1)^{-1} (P_0/P_1)^K - 1] \right. \\ &\quad \left. - P_1 [(\kappa+1)^{-1} - 1] \right\} \end{aligned}$$

