AIR MODIFICATION DUE TO A STEP CHANGE IN SURFACE TEMPERATURE*

H. F. VUGTS
Dept. of Meteorology, Free University, Amsterdam, The Netherlands

and

J. A. BUSINGER
Dept. of Atmospheric Sciences, University of Washington, Seattle, Wash., U.S.A.

(Received 3 August, 1976)

Abstract. Air modification due to a sudden increase in surface temperature when the air flows from the sea over a beach exposed to the sun has been studied. The temperature changes were measured as a function of horizontal distance from the step change up to 1000 m and as a function of height up to 12 m. Some simple formulas have been developed to describe the variation of air temperature downwind. The description of the air modification is satisfactory in most cases and only requires knowledge of the step change in surface temperature, the wind velocity and the roughness length.

1. Introduction

When air flows from the sea over a dry sandy beach exposed to strong solar radiation, it encounters a sudden increase in surface temperature. The roughness of the water and of the beach are of the same magnitude so the transition is largely thermal. The air modification as a result of such a transition is the subject of this study.

The north beach of the island Schiermonnikoog in the Netherlands (53°30′ N, 6°10′ E) provided a nearly ideal site because it is extensive and nearly horizontally uniform. During the fair weather period from 7–12 June 1975, the air over the sea was nearly in equilibrium with the underlying surface and appeared to be close to neutral in the lower part of the boundary layer. Consequently, when this air traveled over the beach, an almost steady-state condition of air modification occurred and a substantial data set could be obtained in a relatively short time. The internal boundary layer that develops in this type of situation has been studied to some extent but relatively few observation sets have been published. Comparable experimental work has been done by Hsu (1973) who studied the temperature and wind profiles in the surface layer over a beach. Several theoretical models have been proposed, e.g., Philip (1959), Townsend (1965), and Taylor (1970). Philip and Townsend made simple assumptions concerning the behavior of the eddy-transfer coefficients and the stratification of the incoming air. Taylor developed a more detailed numerical model which describes the air flow in the lowest hundred metres of the atmosphere above changes in surface roughness and

* Contribution Number 389, Department of Atmospheric Sciences, University of Washington.

temperature or heat flux, based on boundary-layer approximations, the Businger-Dyer description of the surface layer, and a mixing-length hypothesis.

Although the Businger-Dyer description is strictly valid only for horizontally uniform conditions and its use for modeling the internal boundary layer is questionable, as Taylor himself points out, we have also used it in the present paper for fitting the profiles. However, a correction function is introduced to accommodate the strong divergence of the heat flux which takes place in the lowest 2 m.

It turns out that the observed air modification can be described with simple interpolation formulas using only the step change in surface temperature, the wind velocity at, e.g., 2-m height, and the roughness length.

2. Experimental

At the measurement site, the width of the beach is about 400 m, measured from the high-tide level to the first dunes. Over this distance the surface is slightly inclined rising about 1 m; the beach surface is most of the time uniform, except during periods (of at least a few days) when the wind is blowing continuously from one direction, then barcans develop with a maximum height of about 0.5 m. During the experimental period, barcans were absent except on the last day when they developed over part of the fetch.

To investigate the changes in temperature as a function of height and distance downwind, three masts for measuring temperature profiles were erected. Each provided temperature values at five levels, 1.0, 2.5, 5.0, 9.0 and 12.5 m above the ground. The sensing elements were thermistors shielded against radiation and naturally ventilated. For all the runs investigated, the wind velocity was at least 4 m s^{-1}. Between the three tall masts, a row of small masts was set up for measuring the air temperature at a height of 2.5 m. Also the water temperature and the air temperature about 4 m above sea level were recorded; see Figure 1. Every 5 min all the temperatures were recorded on three strip-chart recorders, whose recordings were checked against those from separate thermographs situated near the three 12-m masts.

Near mast II, wind-velocity profiles were measured with anemometers at levels of 0.5, 1.0, 2.0, 3.0 and 5.0 m, and readings were made during daytime every half hour. Also wind velocity and wind direction were continuously registered at a level of 2.0 m. Near mast II, continuous surface temperature recordings were carried out at two places, and during the day every half hour a series of 15 readings were made along the array of masts with an infrared thermometer.

3. Results

During the period from June 7–12, 1975, the weather was good: each day the situation was favorable for the study of air modification, i.e., there was an air flow

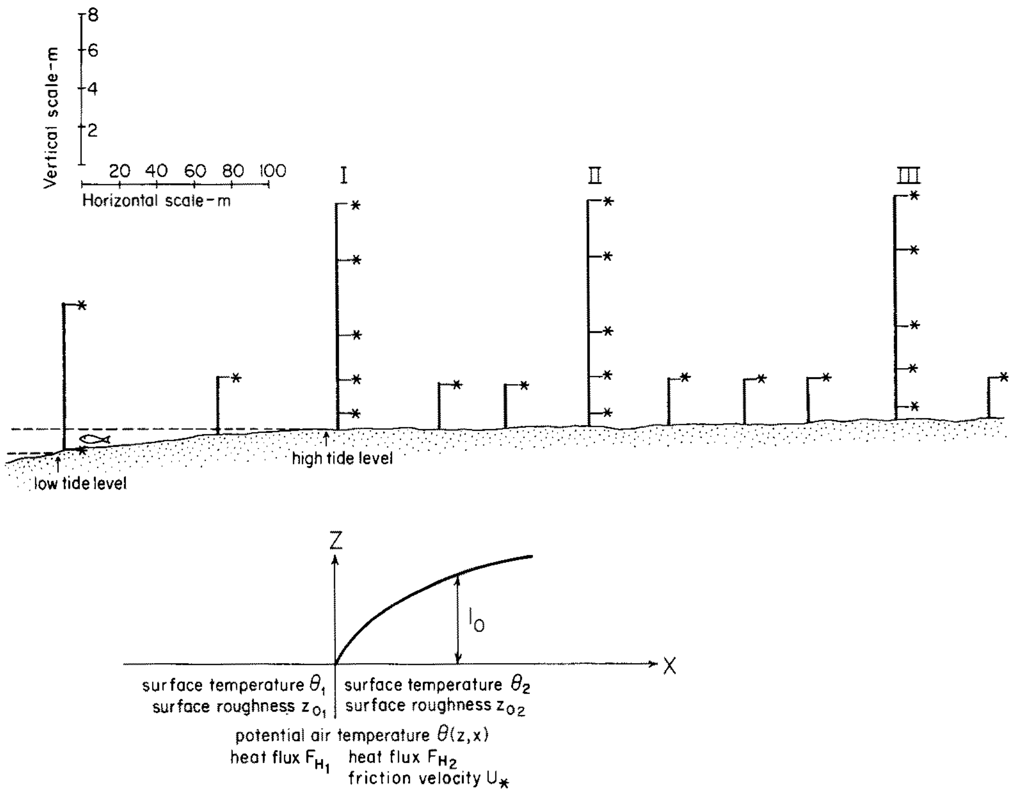

Fig. 1. Schematic diagram of the array of towers and the formation of the internal boundary layer.

from the cold sea to the heated beach. There were no clouds, the global radiation was more than 26 MJ m^{-2} per day, and the observations were more or less complete.

From the temperature recordings for each series of 12 measurements, a mean hourly value was calculated to the nearest hundredth of a degree centigrade. (It will be apparent that absolute accuracy is not so important as the relative accuracy.) Figure 2 shows a typical example of an actual hourly temperature average. At the bottom of the figure the surface temperatures have been indicated; also the mean value (30 °C). The coastal water temperature was 16 °C while the open sea water temperature measured at a light-vessel was 14 °C. An increase of a few degrees was observed along the wet beach between the tide line and the high-tide level (about $x = 0$ m). The figure also shows that the temperature increase of the air at 1.0 m (about 1.5 °C) is about two times the increase at 12.5 m (0.7 °C) over a distance of about 400 m. Mean hourly values were also obtained for the surface temperature, wind velocity and wind direction.

From the daytime wind-profile measurements, it was impossible to find a consistent z_0 value due to the wide scatter in the z_0 data. Although z_0 values obtained from near-neutral profile data during the night are more consistent, the

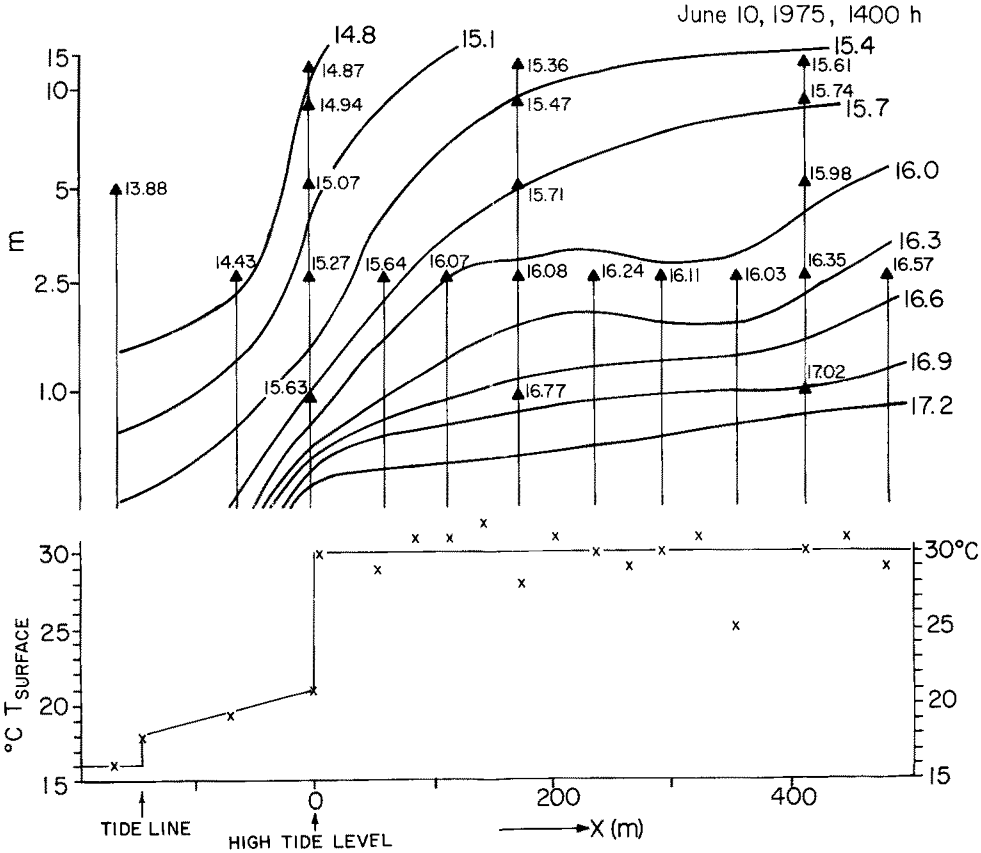

Fig. 2. Vertical section of the temperature observation on June 10, 1975, 1400 LST. Actual points of measurement are indicated by ▲. The surface temperature measurements are indicated by ×.

scatter is still unmistakable. This is due to the fact that over very smooth surfaces the zero intercept has a large uncertainty. The best mean value obtained from the near-neutral runs is $z_0 = 40\ \mu$m, which differs very little from values obtained in situations when the air flow did not come from the sea, and is comparable with values given by Hsu (1971). It may be concluded then that the wind profile has adjusted to the new surface conditions at $x/z_0 \simeq 5 \times 10^6$, which is comparable with values indicated by Rao *et al.* (1974) and Taylor (1969).

The wind speed and temperature profiles from the three 12-m masts were obtained by a least-square fit using non-dimensional wind speed and potential temperature gradients and the Businger-Dyer representations with $\gamma = 16$ and $k = 0.4$; see Paulson (1970). For the temperature profiles, the observations at the five levels were used, together with the surface temperature, which is assumed to be the temperature at the z_0 level. For the wind profile, the values at 2.0 m were used with $z_0 = 40\ \mu$m. From the profiles obtained in this way, the Obukhov length L, the friction velocity u_* and the heat flux F_H were calculated.

Theories and experiments concerning air modification can be divided roughly into two groups. One group deals with the horizontal scale 0–20 m; see, e.g., Rider *et al.* (1963), who studied the air modification at a tarmac-grass boundary to a downwind distance of 16 m and a height up to 1.5 m. The other group concerns a scale of 10 km or more; see, e.g., Malkus and Stern (1953), who studied the air modification at a water-land boundary to a downwind distance of 10 km and a height up to 2000 m. Relatively little work has been published concerning a scale 0–1000 m. In this area the most detailed reports are those published by Taylor (1970, 1971), who constructed a numerical model. From our measurements (see, e.g., Figure 2), it is clear that the order of temperature change predicted by Taylor for the first 1000 m agrees well with our observations.

The attempt now is to describe the development of the temperature profile, starting from mast I, to masts II and III with simple empirical relations and common meteorological observations. This means in our case: wind velocity at 2 m, surface temperatures and knowledge of z_0.

A. The heat flux

From the heat fluxes calculated for masts II and III, it appeared that the fluxes derived from profiles II are always greater than or equal to the fluxes from profiles III. The differences are from 0 to about 5%. Due to the fact that the air is warmed with increasing distance from the coast, the heat flux will decrease, which is, however, only a few per cent in the first 1000 m.

Now we assume that the heat flux can be written as:

$$F_{H_2} = \alpha \rho c_p u_2 (\theta_2 - \theta_1), \tag{1}$$

where:

ρ = density; kg m^{-3},
c_p = specific heat at constant pressure; $\text{J °C}^{-1} \text{kg}^{-1}$,
u_2 = wind velocity at 2.0 m; m s^{-1},
$\theta_2 - \theta_1$ = step change in surface temperature; °C
α = constant.

The correlation diagram is given in Figure 3, using 60 values, calculated for mast II. The constant α seems to be 2.088×10^{-3}, which is in close agreement with a value given by Fleagle and Businger (1963), derived for large-scale air modification.

B. The air temperature change

From the numerical model proposed by Taylor (1970) and the numerical modeling of the planetary boundary layer given by Estoque (1973), it is expected that the height $l_0(x)$, above which the temperature is not affected by the change in surface temperature, is of the order of 100–200 m when x is between 200 and 1000 m. According to Townsend's formula (1965) for the internal boundary layer, l_0 would be about 25 m. This value seems too small, because the intercept of our

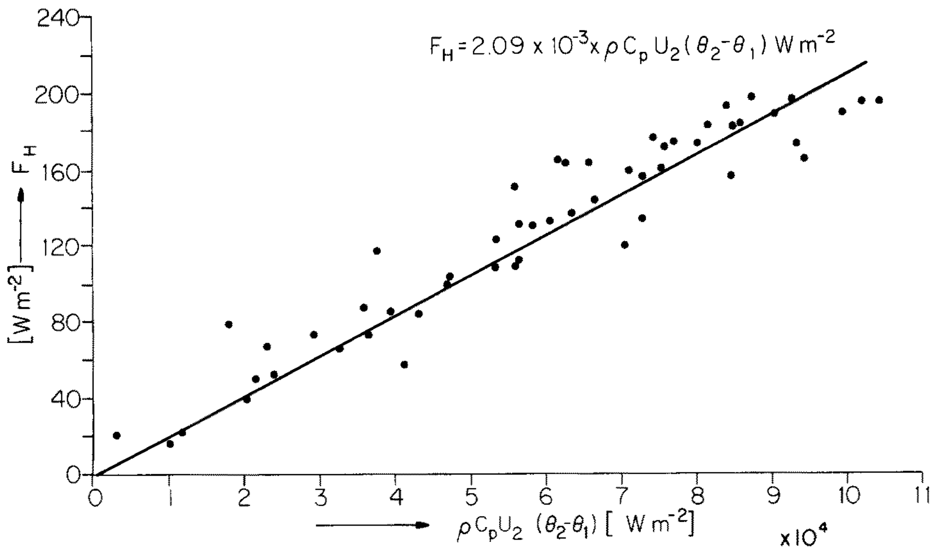

Fig. 3. Heat-flux correlation diagram calculated with Equation (1).

observed temperature profiles appears to be at a level of 100 m at least. Nevertheless it is attractive and feasible to use formulas similar to those used by Townsend (1965) to predict the temperature change observed by Rider *et al.* (1963).

Assume that the internal boundary-layer thickness $l_0(x)$ is given by

$$x = K_1 l_0(x) \ln\left\{\frac{l_0(x)}{z_0}\right\}, \tag{2}$$

where K_1 is a constant (= 0.23 in our case). The shape of this curve is close to $x^{0.8}$ which is often given for the growth of the internal boundary layer. Assume further that after a step change in surface temperature, the temperature profile changes logarithmically. The potential air temperature at a distance x and a height z is then given by:

$$\theta(x, z) = \theta(0, l_0) - \frac{\log_{10} e\, F_{H_2}}{k u_* \rho c_p} \ln\left(\frac{z}{l_0}\right), \tag{3}$$

where:

$\theta(0, l_0)$ = the extrapolated potential temperature at height l_0 from profile I,
u_* = the friction velocity of the downstream air flow,
k = the von Kármán constant,
z = height,
l_0 = the height defined by Equation (2).

If we substitute the values of F_{H_2} and u_*, obtained from our fitted profiles II and III, it is not possible to find a completely consistent description of the profiles at masts II and III with Equations (2) and (3). The best compromise was obtained when K_1 was taken to be 0.23. Further it appeared that the extrapolated values of $\theta(0, l_0)$ differ no more than a few tenths of a degree from the measured values above the sea. Forty-five profiles each were calculated for both masts with Equation (3). Then the deviations were computed between the observed profiles and the profiles predicted from Equation (3). These deviations were calculated as a correction on $\ln(z/l_0)$ and were carried out for the respective z values. The results were grouped in successive classes of the Obukhov length, L, with width 1.0, 2.0, or 3.0 m, in such a way that each group contained at least four calculated deviations. The mean values of the groups are given in Figure 4 as a function of $-L$, and separated for each level of z. For every level, a least-square fit of the form $y = a + b \ln(-L)$ was calculated, where y is the deviation in units of $\ln(z/l_0)$ and a and b are constants. These lines are also drawn in Figure 4. The five curves

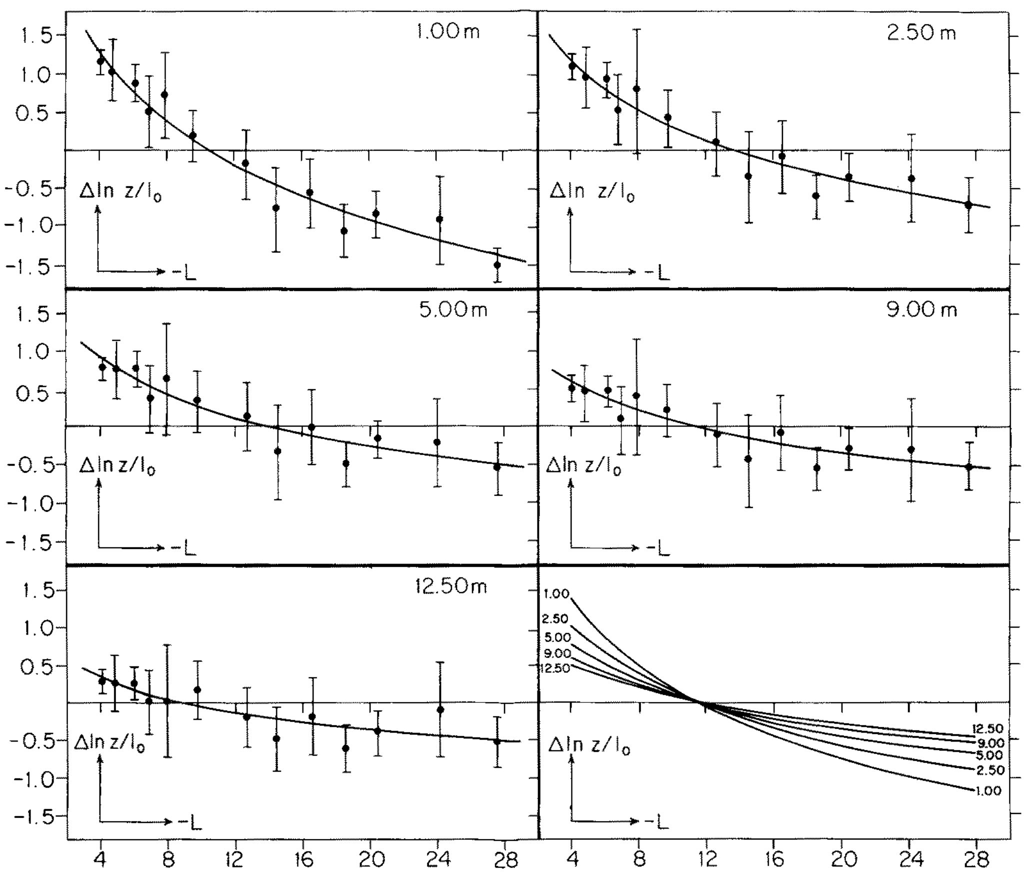

Fig. 4. Deviations between measured and predicted profiles calculated with Equation (3) in units of $\ln(z/l_0)$ versus $-L$ for the various z levels. Full line is the least-square fit of the form $y = a + b \ln(-L)$. The correction functions calculated by means of Equation (4) for the corresponding z levels.

obtained in this way can be described numerically by a function of the form:

$$K_2\sqrt{\frac{z_0}{z_*+z}}\left\{K_3-\ln\left(\frac{-L}{z_0}\right)\right\} \tag{4}$$

with $z_* \simeq 1.0$ m, $K_2 = 298$, $K_3 = 12.57$ and $z_0 = 40$ μm. These correction functions for the different heights are also given in Figure 4.

The introduction of z_*, which is necessary as a boundary condition for $z \to 0$, may be explained as follows. In fitting the profiles, it is implicitly assumed that the heat flux is constant with height. In the situation described here, with a step change in heat flux, it is to be expected that the heat flux varies with height,

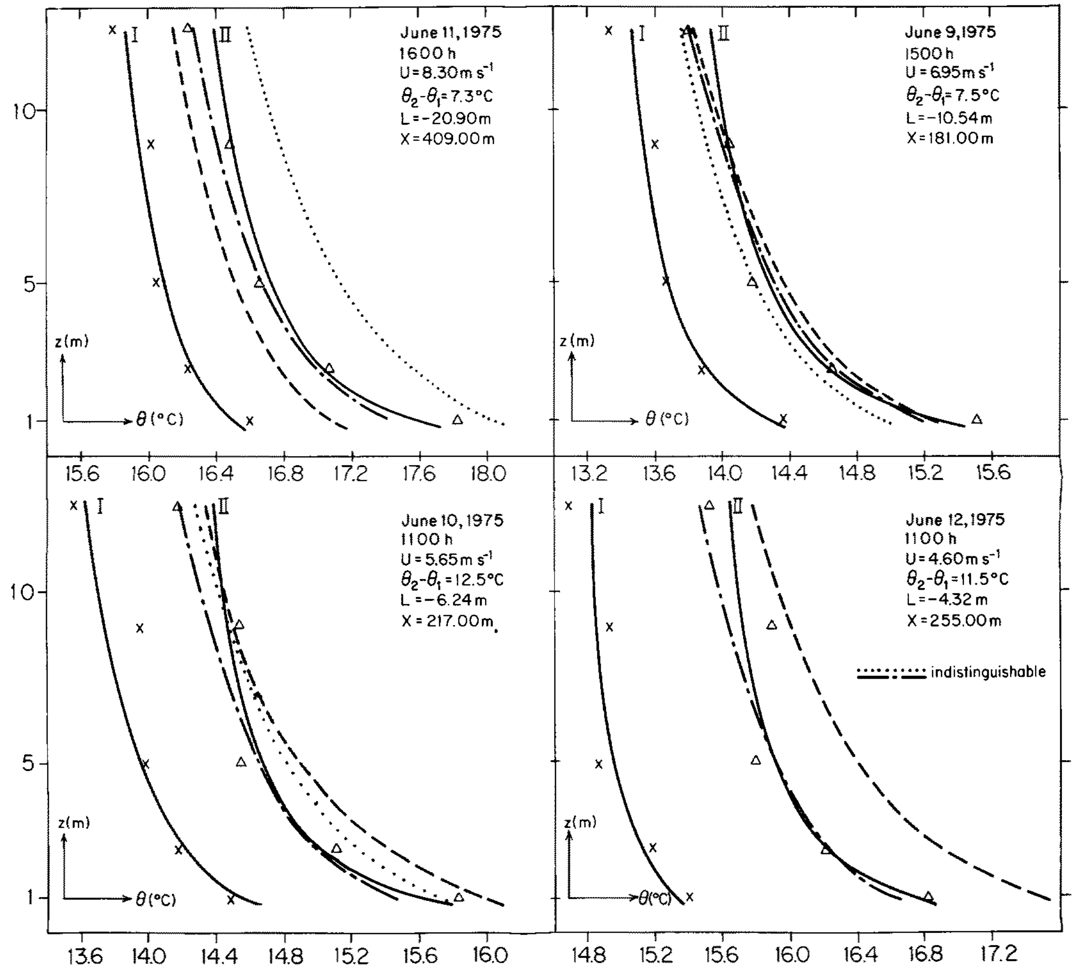

Fig. 5. Measured and calculated temperature profiles for four different stability situations. ×: measured potential air temperature, mast I; ——— I: fitted profile, mast I; △: measured potential air temperature, mast II; ——— II: fitted profile, mast II; - - - -: predicted profile, mast II, with Equation (3); -·-·-·: predicted profile, mast II, with Equations (3) and (4); ....: predicted profile, mast II, with Equation (5) and estimated values of F_{H_2}, u_* and L.

having high values near the surface and decreasing to the original value at a higher level. Probably the divergence of the heat flux decreases rapidly from the surface to a height z_*. This is supported by the measured profiles, as shown in Figure 5; above 2.5 m, profiles I and II are nearly parallel. In unstable conditions with $(z/-L)>\frac{1}{20}$, it is possible to neglect z_* in Equation (4). A comparable boundary condition which can be derived if z_* is not introduced is: $(z/l_0)\gg(z_0/z)$, which means that the description fails close to the ground.

To show how the correction functions influence the temperature profiles, four situations each with different stability are given in Figure 5. The measured profiles of masts I and II are shown, together with the predicted profiles for mast II calculated with Equation (3), and the corrected profiles after application of Equation (4). From these profiles, it is clear that application of the correction improves the agreement with the measured profiles. However, extrapolating the temperatures to z_0 by means of Equations (3) and (4) gives erroneous results, which occurs in many other theories also.

C. Prediction of Air Modification by Simple Measurements

Our goal was to predict the change of the temperature profiles by simple measurements. For this purpose we use Equations (3) and (4) together:

$$\theta(x,z)=\theta(0,l_0)-\frac{\log_{10}e\,F_{H_2}}{ku_*\rho c_p}\left[\ln\left(\frac{z}{l_0}\right)+K_2\sqrt{\frac{z_0}{z_*+z}}\left\{K_3-\ln\left(\frac{-L}{z_0}\right)\right\}\right]. \tag{5}$$

The meteorological parameters are estimated as follows:

(i) The heat flux is given by Equation (1). If the accuracy of $(\theta_2-\theta_1)$ is about 1 °C, representing about 10% in most cases, and that of u_2, about 0.2 m s^{-1} for the mean hourly values, then the error in F_{H_2} will be about 15%.

(ii) The friction velocity u_* can be estimated with the equation:

$$u_2=\frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{6}$$

which differs 3 to 7% from the u_* obtained by fitting the profiles with the appropriate formulas.

(iii) The Obukhov length can be estimated by equating it to the Richardson number:

$$\frac{z}{L}=\frac{g}{\bar{\theta}}\frac{\partial\bar{\theta}/\partial z}{(\partial\bar{u}/\partial z)^2}=\mathrm{Ri}. \tag{7}$$

We substituted for $\partial\bar{\theta}/\partial z$: $\theta_1-\theta_2=\mathrm{d}T$ the step change in surface temperature and $\mathrm{d}z=4$ m; $\partial\bar{u}/\partial z$ was calculated with Equation (6) for the level $z=2$ m while $\bar{\theta}=\theta_1+273.15$. The result is given in Figure 6 where the best fit for L corresponds to:

$$L=8.25\frac{1}{\mathrm{Ri}}. \tag{8}$$

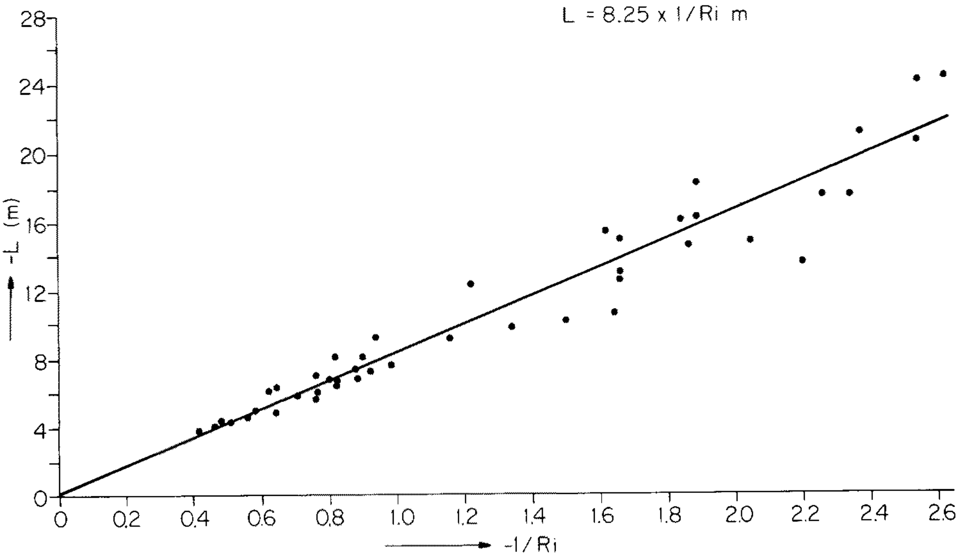

Fig. 6. The Obukhov length as determined by Equation (7).

The error in L will be about 10%, due to the error $\theta_1 - \theta_2$.

With the estimates described in (i), (ii) and (iii), modified temperature profiles were calculated. The results are also given in Figure 5. As expected, the error will be about 25%, which means in the situations given: $\pm 0.3 - 0.4$ °C. This is confirmed by Figure 5. On June 11 the prediction is bad, on the other days there is close agreement between observed and calculated values.

3. Conclusions

(1) From our measurements, it can be concluded that the air modification due to a step change in surface temperature may be described satisfactorily by a simple Equation (5).

(2) If the wind velocity at 2.0 m, the change in surface temperature, the roughness length z_0 and the incoming profile are known, the air modification can be estimated with reasonable accuracy. An improvement in the accuracy of the surface temperature measurement would improve the prediction significantly.

Acknowledgement

Our thanks are due to Mr Ron Lindsay for helping in the computer calculations and to Mrs Ilze Schubert for typing the manuscript. The manuscript was prepared during the visit of the first author at the Department of Atmospheric Sciences, University of Washington, which was made possible by a grant of the Niels Stensen Stichting. Support of the National Science Foundation under Grant ATM76-00855 is also acknowledged.

References

Estoque, M. A.: 1973, in D. A. Haugen (ed.), *Workshop on Micrometeorology*, Amer. Meteorol. Soc., Chapter 6, pp. 217–270.

Fleagle, R. G. and Businger, J. A.: 1963, *An Introduction to Atmospheric Physics*, Academic Press, New York, p. 206.

Hsu, S. A.: 1971, 'Measurement of Shear Stress and Roughness Length on a Beach', *J. Geophys. Res.* **76,** 2880–2885.

Hsu, S. A.: 1973, 'Dynamics of the Sea Breeze in the Atmospheric Boundary Layer: A Case Study of the Free Convection Regime', *Monthly Weather Rev.* **101,** 187–194.

Malkus, J. S. and Stern, M. E.: 1953, 'The Flow of a Stable Atmosphere over a Heated Island', *J. Meteorol.* **10,** Part I: 30–41; Part II: 105–120.

Paulson, C. A.: 1970, 'The Mathematical Representation of Wind Speed and Temperature Profiles in the Unstable Atmospheric Surface Layer', *J. Appl. Meteorol.* **8,** 857–861.

Philip, J. R.: 1959, 'The Theory of Local Advection: I', *J. Meteorol.* **16,** 535–547.

Rao, K. S., Wyngaard, J. C., and Coté, O. R.: 1974, 'The Structure of the Two-Dimensional Internal Boundary Layer over a Sudden Change of Surface Roughness', *J. Atmos. Sci.* **31,** 738–746.

Rider, N. E., Philip, J. R., and Bradley, E. F.: 1963, 'The Horizontal Transport of Heat and Moisture - a Micrometeorological Study', *Quart. J. Roy. Meteorol. Soc.* **89,** 507–531.

Taylor, P. A.: 1969, 'The Planetary Boundary Layer above a Change in Surface Roughness', *J. Atmos. Sci.* **26,** 432–440.

Taylor, P. A.: 1970, 'A Model of Airflow above Changes in Surface Heat Flux, Temperature and Roughness for Neutral and Unstable Conditions', *Boundary-Layer Meteorol.* **1,** 18–39.

Taylor, P. A.: 1971, 'Airflow above Changes in Surface Heat Flux, Temperature and Roughness; an Extension to Include the Stable Case', *Boundary-Layer Meteorol.* **1,** 474–497.

Townsend, A. A.: 1965, 'The Response of a Turbulent Boundary Layer to Abrupt Changes in Surface Conditions', *J. Fluid Mech.* **22,** 799–822.