The Influence of Soil Characteristics on the Development of the Planetary Boundary Layer

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RESUMEN

Para estudiar la importancia de ciertas características del terreno desde el punto de vista del balance energético en la superficie y su influencia sobre la interacción aire-suelo en las capas bajas de la atmósfera, se ha utilizado un modelo unidimensional de alta resolución de la capa límite planetaria (PBL). Mediante un test de sensibilidad se observa que la humedad disponible del suelo es un parámetro decisivo en el calentamiento diurno del aire, mientras que la inercia térmica del substrato ejerce una influencia considerable en el enfriamiento nocturno. También se han analizado otros parámetros del suelo, tales como el albedo, la rugosidad y la emisividad en onda larga, siendo su influencia aparentemente menos importante.

También se ha prestado atención al modelado del intercambio vertical turbulento en el caso de una intensa convección seca, que es un fenómeno típico de terrenos áridos durante la época estival. A este fin se ha aplicado el modelo unidimensional con diferentes esquemas de parametrización del intercambio convectivo en la PBL. Los resultados de tales simulaciones se han comparado con observaciones reales realizadas en la región central de la península Ibérica.

1. INTRODUCTION

There is increasing concern in meso-meteorological modelling with respect to the influence of different soils on the atmospheric processes occurring above them. It is broadly admmited that a lack of homogeneity in the energy balance of the soil may give rise to local atmospheric circulations (Walker and Rowntree, 1977; Mahrer and Pielke, 1978; Segal *et al.*, 1983;

Benjamin and Carlson, 1986). For this reason it is extremely important that an accurate parameterization of the characteristics of the soil should be available, for incorporation into meso-scale meteorological forecasts, in which special attention is given to the processes occurring in the planetary boundary layer (PBL) (Zhang and Anthes, 1982).

The present article describes the application of a high resolution one-dimensional model of the PBL, in which great importance is given to thermal and moisture fluxes close to the ground. The aim is to underline the importance of accurate knowledge of soil types when attempting to forecast the values of meteorological variables close to the earth's surface, as well as of also predicting the height of the PBL, which is a very important magnitude in the development of certain meteorological and atmospheric pollution processes. Therefore, an attemp will be made to determine which physical parameters of the soil should be given special attention, due to their determinant influence on the atmospheric variables of the PBL.

Likewise, it has been observed that the parameterization of the PBL used in the model does not allow the atmospheric surface layer with a superadiabatic thermal gradient, typically formed under conditions of intense ground heating, to exceed more than a few tens of metres in thickness. This result does not coincide with what is normally observed in the central region of the Iberian peninsula during the summer months, where the atmospheric radiosondes performed at midday oftenly show unstable thermal gradients at levels up to 300 m or more, and which probably reach higher levels during the afternoon. Although we have not found a clear explanation for this behaviour, a relation with the semi-arid nature of the region, giving rise to excessive surface heating, seems to be the most plausible hypothesis.

The above has led to consideration of two possible modifications to the procedure applied in the model used for treatment of atmospheric processes in the PBL under conditions of free convection. The results thus obtained were compared to actual values from radiosondes performed at Madrid airport on a representative summer day. This analysis would appear to suggest that in cases of intense dry convection it might be advisable to consider certain adjustments in modelling energy exchange between the lower layers of the atmosphere, depending on the specific characteristics of the soils.

2. DESCRIPTION OF THE MODEL

The one-dimensional model used includes 10 layers whose thickness increases with altitude, such that resolution is greater closer to the ground (figure 1). Vertical extension of the column is not fixed, although it was decided to establish its upper extreme at around 400 hPa, while pressure at ground level depends on the geopotential height of the surface. The substrate is divided into two parts: a slab in contact with the atmosphere, in which the energy budget will be evaluated, and beneath this a semi-infinite subsoil at a constant temperature Tm. Initially, the possibility of taking into account several substrate layers, like Sasamori (1970), was considered, but it was finally decided not to complicate the model, as generally speaking the temperature at a depth of 1 metre varies only very little throughout the day (Kuo, 1968).

Calculation of the energy balance at the surface and parameterization of turbulence and convection are based on the high-resolution model developed by Blackadar (1978). In general the one-dimensional model of the PBL is similar to that used by Zhang and Anthes (op. cit.), although more detailed treatment is given to the long-wave radiative fluxes in the different layers considered. In this way, an important improvement has been achieved, since our model allows the formation and upwards progression of nocturnal radiative inversions. The model is briefly described below, submiting the reader to Zhang and Anthes paper for more details. Attention will be only paid here to the description of long-wave radiative exchange parameterization added as well as alternative methods of PBL free-convection modelling considered.

2.1. Soil energy balance

The temperature of the ground T_g is derived following the Blackadar's (1976) «force-restore» slab model by means of the equation:

$$C_g \cdot \frac{\partial T_g}{\partial t} = R_n - H_m - H_s - L_v E_s$$

where C_g is the thermal capacity of the slab per unit area ($J\,m^{-2}\,K^{-1}$), R_n the net radiation, H_m the heat flux into the substrate, H_s the sensible heat given up to or received from the atmosphere by turbulence, L_v the latent heat of evaporation and E_s the moisture flux between the ground and the lowest layer of air in the model. All these terms are functions of soil characteristics:

- C_g and H_m depend on the so-called «thermal inertia» (P), which is a function of the thermal conductivity and heat capacity of the soil.
- R_n depends on surface albedo (A), for the short-wave component, and on long-wave soil emissivity (ε_g),
- H_s depends on roughness length (z_0), and
- L_v E_s depends on roughness length as well as on the «moisture availability» of the soil, a normalized parameter ranging between 0 (water) and 1 (dry soil).

2.2. Parameterization of the Planetary Boundary Layer

Planetary boundary layer (PBL) fluxes are calculated by means of the high-resolution model of Blackadar described by Zhang and Anthes (op. cit.).

In this parameterization the PBL structure is classified in four types of turbulent conditions based on the bulk Richardson number:

$$Ri_B = \frac{g\, z_a\, (\theta_{va} - \theta_{vg})}{\theta_a\, V_a^2}$$

where θ_{va} and θ_{vg} are the virtual potential temperatures in the lowest layer of the model and at ground level respectively, z_a is the height of $k = 1/2$ level and V_a is the horizontal wind speed at the lowest model layer.

The four cases considered are: stable, mechanically driven turbulence, forced convection and free convection. In the first three of these cases the turbulent exchange of heat, moisture and momentum above the lowest layer of the model are calculated by a first-order closure approach (K-theory). However, in the fourth case the treatment given by the model consists of assuming that vertical mixing does not depend on the value of the gradients between adjacent layers, but on the thermal structure of the entire PBL. In other words, exchange is assumed to occur between the lowest layer and each layer in the PBL instead of between adjacent layers (figure 1).

Therefore, above the lowest layer, the rate of change of any pronostic variable α at $k + 1/2$ level will be given by

$$\partial \alpha_{k+1/2}/\partial t = \overline{m} \cdot w(z) \cdot (\alpha_a - \alpha_{k+1/2})$$

where $m(z) = \overline{m} \cdot w(z)$ is a so-called mixing coefficient, introduced by Estoque (1968), which represents the fraction of mass exchange between k level and the lowest layer per unit time, being $w(z)$ a weighting factor. The heat flux at any level in the mixed layer can be determined using the principle of heat energy conservation:

$$\frac{\partial \theta}{\partial t} = \overline{m} \cdot w(z) \cdot (\theta_a - \theta) = -\frac{1}{\rho\, C_{pm}}\, \frac{\partial H}{\partial z}$$

which leads to

$$H_k = H_1 - \overline{m} \cdot [\,\rho \cdot C_{pm} \cdot \int_{z_1}^{z_k} \rho \;\; C_{pm}\, w(z) \quad [\theta_a - \theta(z)\,] \cdot dz$$

which, assuming no energy flux across the top of the mixed layer, becomes:

$$\overline{m} = H_1 \cdot [\,\rho \cdot C_{pm} \cdot (1 - E) \cdot \int_{z_1}^{z_m} w(z) [\theta_a - \theta(z)\,] \cdot dz\,]^{-1}$$

where C_{pm} is the specific heat for moist air, z_m is the nonbuoyancy level, H_1 is the heat flux at the top of the lowest layer, calculated by means of the

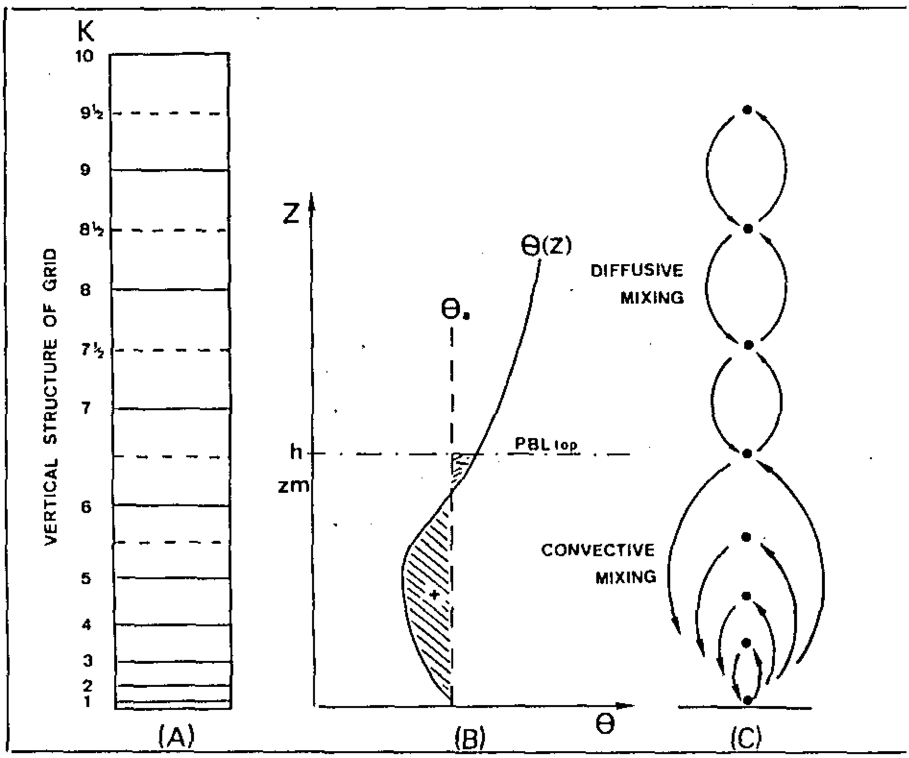

Figure 1.—(a) Vertical grid structure of the model. (b) Positive and negative areas asociated with an adiabatic ascent from the lowest layer. (c) Illustration of vertical exchanges between layers in the classical K-Theory and the free-convective mixing scheme used in the model.

Priestley equation (Priestley, 1956) and E is a so-called «entrainment coefficient» above the non-bouyancy level denoting the fraction of the bouyant energy available for entraiment above z_m (see fig. 1). In the present case, following Zhang and Anthes (op. cit.), a value of 0.2 has been chosen.

2.3. Parameterization of long-wave radiative flux

The inclusion of the calculation of long-wave radiative flux divergence in each layer has shown to be of great importance, even without the presence of clouds as the modeled case. In this respect, the procedure followed consist in calculating the upward and downward radiative fluxes at the top and the base of each layer by means of the well known formulas (Sasamori, 1972):

$$F_u(z) = B(0) + \int_0^z A(z, \zeta) \cdot \frac{\partial B}{\partial \zeta} \cdot d\zeta$$

$$F_d(z) = B(Z_t) - \int_z^{z_t} A(z, \zeta) \cdot \frac{\partial B}{\partial \zeta} \cdot d\zeta$$

After the fluxes have been calculated the balance in each level is performed by the equation:

$$\frac{\partial T_{k+1/2}}{\partial t} = \frac{Fu_k - Fu_{k+1} + Fd_{k+1} - Fd_k}{\rho_{k+1/2} \cdot Cp_{k+1/2} \cdot \Delta_k z}$$

where the subscript $k+1/2$ refers to the center of the layer between k and $k+1$ levels (fig. 1), $A(z, \zeta)$ is the absorption function of the layer between z and ζ (the values of water vapor and CO_2 absorptivities are those tabulated by Mahrer and Pielke, 1977), B is the so-called source function and $\Delta_k z$ is the depth of the layer comprised between k and $k+1$ levels.

Logically, this procedure does not allow the upward and downward radiative fluxes respectively at the lower and upper limits of the model to be calculated. The first of these must be the sum of the flux emitted and reflected by the ground, i.e.:

$$\varepsilon_g \cdot \sigma \cdot T_g^4 + (1 - \varepsilon_g) \cdot F_d(0)$$

while estimation of the second is an important environmental condition, as a temperature representative of the atmospheric layers located above the top of the model must be assumed.

3. SENSITIVITY OF THE MODEL TO SOIL PARAMETERS

Sensitivity testing of the model included a comparison between the results of the temperature of the ground T_g, the air in the lowest layer of the model T_a and the height of the planetary boundary layer h, for different types of terrain. In this respect, reference values corresponding approximately to the central points of the intervals in which the different soil parameters usually vary were chosen, as shown in Table I. For example, in the case of albedo, a reference value of 0.23 was chosen, this representing a median value between the minimum (0.06) and maximum (0.40) values. Undoubtedly ground covered by snow would attain an albedo close to 0.90; however, this extreme case is not considered in Table I.

Following selection of this reference terrain, the one-dimensional model was systematically applied, modifying in each case a single parameter without altering the rest. This procedure might at first sight seem rather unrealistic as, on the one hand, soil parameters are to some extent interrelated (Philip, 1957; Idso *et al.*, 1975; Ookuchi *et al.*, 1984) and, on the other, their values do not remain constant throughout the day. However, in the present case this

TABLE 1

Soil parameters values considered in the sensitivity test. Low and high values correspond to the extremes of the interval in which they usually vary and reference values are the corresponding arithmetic averages (except in the case of Z_0).

SOIL PARAMETERS	*Low value*	*Reference value*	*High value*
Albedo	0.06	0.23	0.40
Moisture availability	0	0.5	1
Ground emissivity	0.84	0.92	1
Roughness lenght (m)	0.01	0.12	1.5
Thermal inertia (S. I.)	1400	2250	3100

circumstance is not over important as the aim is simply to analyze the individual sensitivity of each parameter in the results of the model.

All of the simulations performed during the sensitivity test were based on the same initial conditions: a specific humidity decreasing linearly with height (from 9 g/kg near the ground to 0 g/kg at 400 hPa) and a constant vertical temperature gradient ($\partial T/\partial z = 0.005$ K/m) at all levels, being the initial lower-layer air temperature $T_a = 293$ K. This was in order to avoid any lack of homogeneity in stratification causing discontinuities in simulation of PBL growth with different types of terrain. Initial vertical profile of wind speed was logarithmic in the first four layers (from 2.7 to 8 m/s) and constant aloft. The simulations started at 00 LST and were performed throughout a 30-hour period. Solar angles corresponded to those of the equinox day at a latitude of 40º.

3.1. Albedo

Figure 2 shows that during the hours of daylight albedo has an appreciable influence on Tg, *Ta* and *h*. As was to be expected, increases in the albedo correspond to a cooling of the ground. However, this cooling (approx. 3 K) was not as pronounced as might initially have been expected, and was even less so in the layer of air adjacent to the ground. Consequently, this effect appears to be mitigated almost totally at night. On the other hand, the height of the PBL is apparently the most affected parameter as, in the range of albedos considered, its value decreased by approximately 30%.

3.2. Available moisture

The results lend weight to the great importance given to this parameter by other authors (Carlson and Boland, 1978; Physick, 1980; Ookuchi *et al.*,

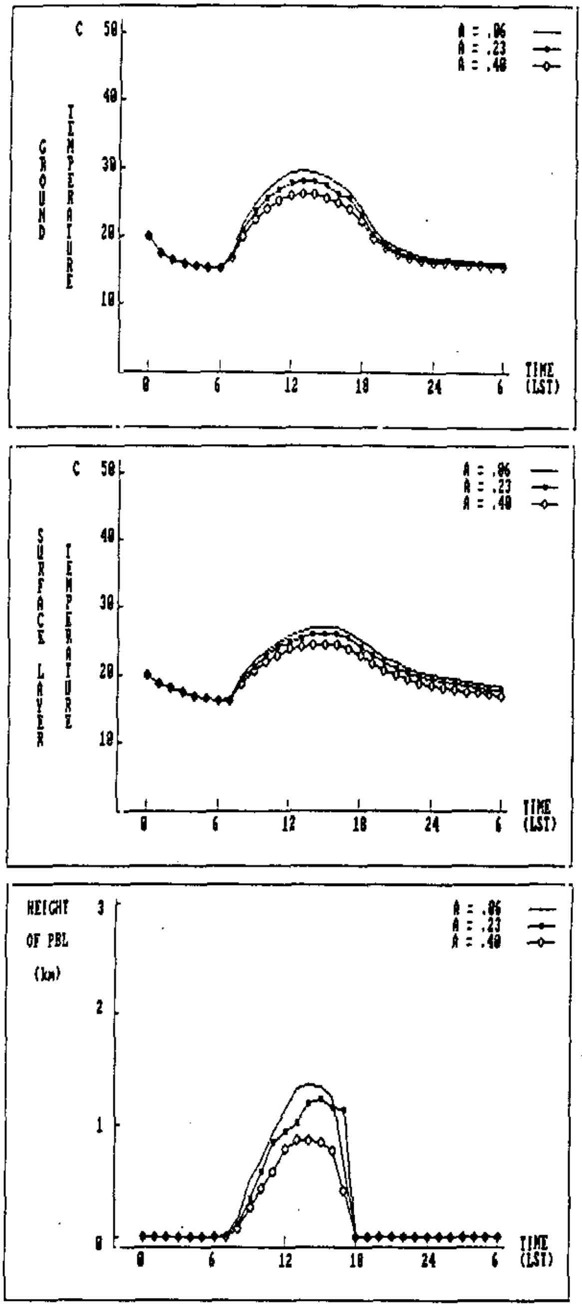

Figure 2.—Daily evolutions of ground and surface layer temperature and PBL depth obtained by the model for three albedo values.

op. cit.). Dry ground reaches very high temperatures during the day, without this heating being compensated during the night. In the case of dry ground lacking vegetation, there is practically no evaporation, consequently the loss of latent heat is minimal. This causes greater heating of the ground and of the adjacent air, which is used to generate intense convection (sensible heat flux), such that the PBL reaches its maximum height at the end of the afternoon. However, in the case of moist ground, the energy received is distributed between the processes of evaporation (latent heat) and of thermal convection (sensible heat). Likewise, the difference in available moisture in the soil appreciably affects growth of the PBL, such that in the range of values considered its maximum thickness undergoes a variation of 100 %, as can be seen in figure 3.

3.3. **Long-wave emissivity**

As it was expected, the effects of the long-wave emissivity of the ground are not appreciable during the day, and consequently do not influence development of the PBL. However, at night this parameter would appear to be less important for the air temperature than for the temperature of the ground (figure 4). This differing behaviour may be explained on the basis of the following reasoning:

The net radiation balance at the surface of the ground at night is expressed via the following equation:

$$R_n = \varepsilon_g \cdot (F_d(0) - \sigma \cdot T_g^4)$$

such that $F_d(0) < \sigma \cdot T_g^4$. In the case of maximum emissivity ($\varepsilon_g = 1$) radiative losses are greater. However, the upward radiative flux arriving at the lowest atmospheric layer from the ground is:

$$\varepsilon_g \cdot \sigma \cdot T_g^4 + (1 - \varepsilon_g) \cdot F_d(0)$$

Consequently, the lower the value of ε_g, the greater will be the cooldown of the air in the surface layer and the smaller the cooldown of the ground. For example, in the extreme case of $\varepsilon_g = 0$, the ground neither emits nor absorbs and consequently its temperature does not vary, while the air in the surface layer continues to lose more energy than it receives and consequently cools down.

3.4. **Roughness parameter**

As can be seen in figure 5, the greater the roughness of the ground the greater the ventilation of the soil, as a result of which it would remain fresher during the day. This might be due to the fact that over rough terrain the latent

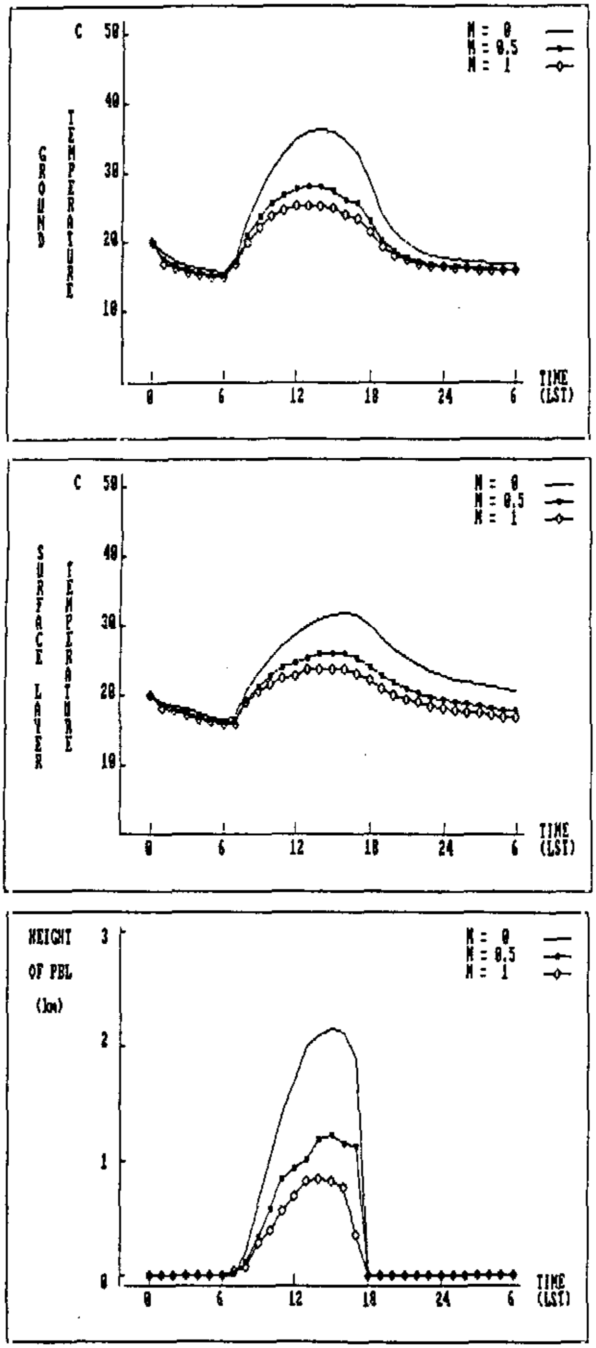

Figure 3.—Same as figure 2, but for soil moisture availability.

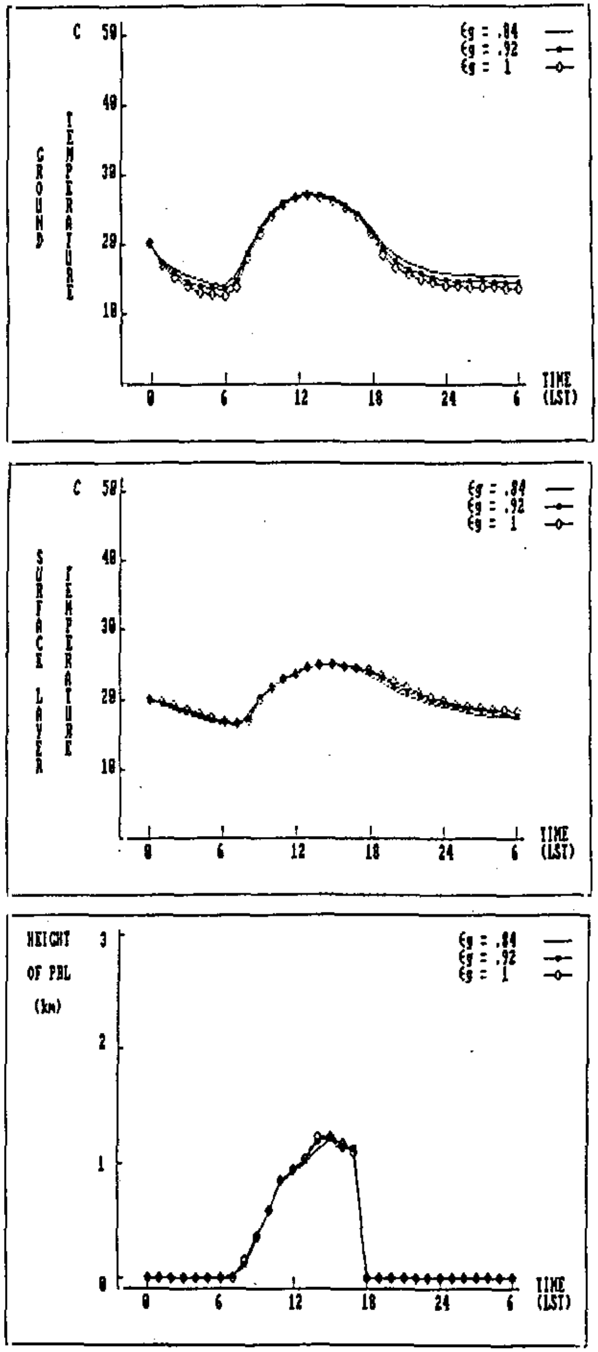

Figure 4. – Same as figure 2, but for soil long-wave emissivity.

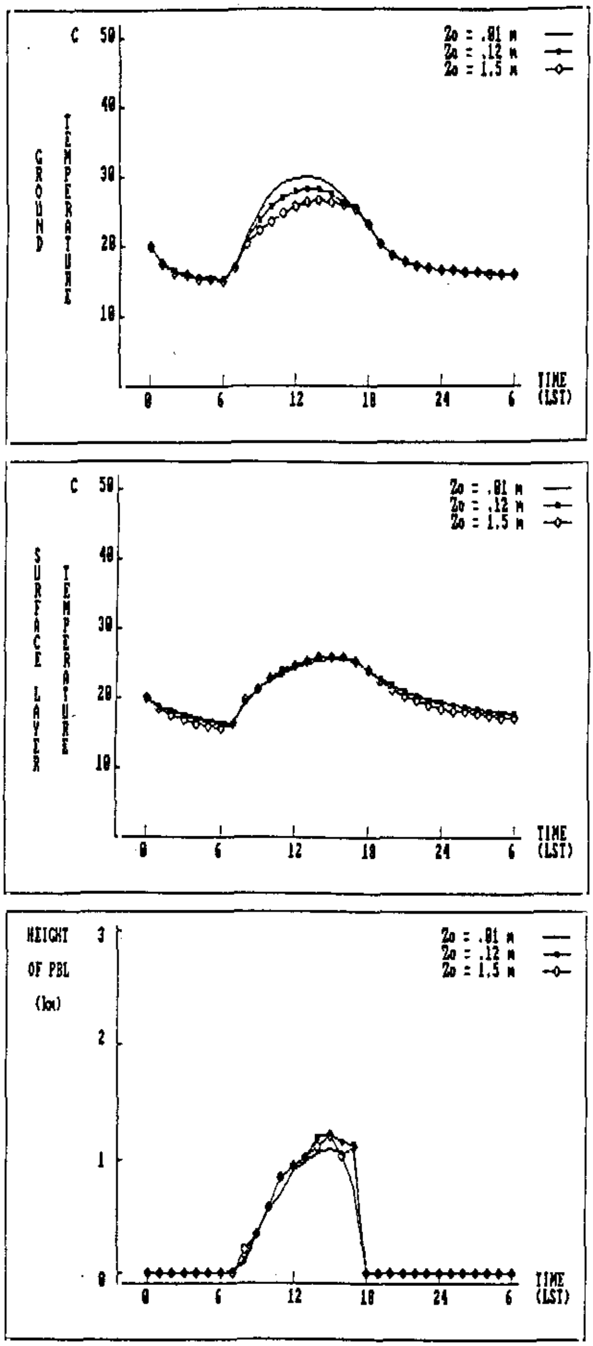

Figure 5.—Same as figure 2, but for soil roughness length.

heat flux from the ground is greater, i.e., the evaporation process is more effective. However, this greater cooldown of rougher ground is not transmitted to adjacent layers of air during the day, nor does it influence development of the PBL. In other words, it would appear that the smaller mechanical turbulence generated by flat terrains allow greater thermal contrast between the air and the ground, such that at a height of a few tens of metres, the effect on air temperature would seem to be independent from the roughness of the ground.

At night, on the contrary, roughness strongly influences the temperature of the surface layer, without ground temperature being affected. Essentially this is due to the fact that the greater mechanical turbulence observed over very rough terrains possibly causes an increase in the sensible heat downward flux, which dampens heat loss in the ground, distributing radiative cooling among the layers of air located above.

3.5. Thermal inertia

As can be seen in figure 6, this parameter is of importance during the night, such that the lower its value, the greater the cooldown of the ground and of the lowest atmospheric layer. However, the greater heat up expected during the day in soils of lower thermal inertia would appear to be rapidly dampened by the instability of the air in the atmospheric surface layer, which gives rise to an important increase in sensible and latent heat fluxes. This effect may be seen more clearly in the development of the PBL during the morning, such that the growth rate of this layer is somewhat faster over terrains of lower thermal inertia. However, this feature of the terrain does not appear to have any significant influence over the maximum height of the PBL.

Consequently, as in the case of roughness commented before, it would appear that stronger nocturnal radiative inversions will be developed over terrains with lower thermal inertia, which is consistent with the urban heat island effect due to, among other things, the lower heat capacity and thermal conductivity (i.e. thermal inertia) of rural terrain.

4. MODIFICATIONS TO CALCULATION OF VERTICAL MIXING IN THE CASE OF FREE CONVECTION

As was pointed out in section 2, in the case of free convection it is assumed that within the PBL the interchange process between the lowest layer and any other located above is modelled by means of a mixing coefficient $[m(z)]$ which, in general, depends on height. As Estoque (1968) pointed out, this coefficient could be related to «...the turbulence characteristics of the atmosphere which, in turn, are related to the large-scale flow pattern and the

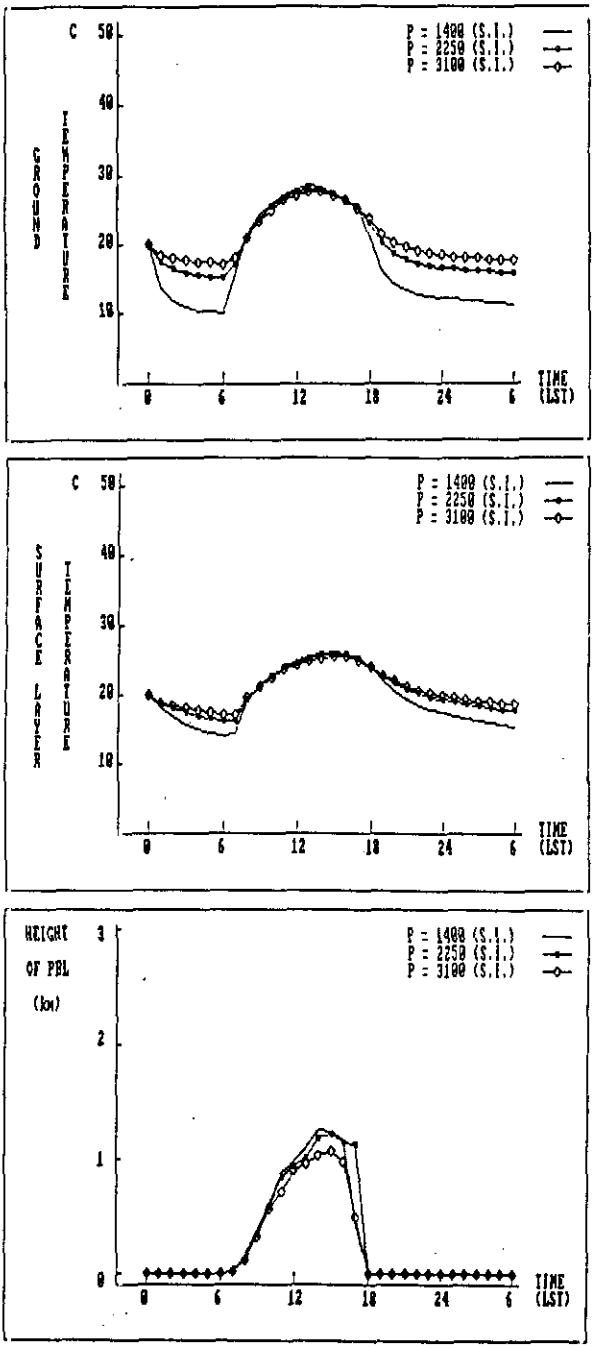

Figure 6.—Same as figure 2, but for soil thermal inertia.

characteristics of the underlying terrain». According with this, he proposed the form

$$m(z)=\overline{m}\left(1-\frac{z}{h}\right)$$

where h is the PBL height. Nevertheless, Blackadar (1978) indicated that the vertical profile of temperature is insensitive to the form of $m(z)$. Therefore, $m(z)$ is set equal to $\overline{m}$. In this case, the mixing coefficient is independent of the height, and, the prognostic variables θ, and V tend to equal out throughout the PBL, except in the lowest layer of the model, where a strong superadiabatic gradient is developed.

This assumption would appear to be logical, as it is generally assumed that convective mixing is «perfect» whitin the PBL. However in arid regions, where in the summer season dry soils tend to reach high temperatures during the middle of the day, it is oftenly observed that the value of the potential temperature decreases with height across a layer of several hundred metres thickness, which does not coincide with the model results above mentioned.

The reason for this typical behaviour might possibly be that the convective mixing throughout the PBL over arid terrain is not as homogeneous as is usually assumed If the phenonemon of atmospheric thermal convection is thought of as being a process produced by elementary warm air parcels or «bubbles» rising from the ground, then it would apparently be logical to assume that as these bubbles rose they would undergo exchange of their masses with the layers of air through which they passed, such that they would gradually dissipate until they completely disappeared at the top of the PBL. Consequently, although the convective mixing would mean that all the layers within the PBL would be influenced by the lowest, the mass exchange with the layers located closer to the ground would be slightly more important than with those located at greater heights. This is consistent with the linear form of $m(z)$ proposed by Estoque (op. cit.).

However, the computed temperature change rate at any level is influenced to a greater degree by $(\theta_a-\theta(z))$ than by $m(z)$. This fact leads us to consider another possible modification to vertical mixing calculation.

In large-scale prognostic models it is normal to introduce a correction factor in order to eliminate excessive superadiabatic gradients, which are not observed at levels distant from the ground. This factor is normally known as the dry-convective adjustment (Anthes and Warner, 1978; Haltiner and Williams, 1980). This procedure consists simply of not allowing the vertical potential temperature gradient to exceed a given critical value (CR). To this end the temperatures in the unstable layers of the model are modified apropriately, the conservation of total potential energy being explicitly maintained. The critical value normally taken into account in the majority of models varies between -0.0004 and -0.001 K/m.

One of the consequences of this purely artificial adjustment is that a part of the calorific energy of the more unstable layers is given up to the upper layers, thus leading to unstable stratification extending progressively upwards, while simultaneously moderating the degree of superadiabaticity.

It has to be noted that, in the present study, the reason of using this adjustment is not directed to eliminate unrealistics superadiabatics gradients, but to allow realistics superadiabatics gradients near ground extend upwards. Although the value of CR could be related to underlying soil characteristics or to the large-scale flow pattern, is this occasion we choose CR = -.007 K/m as a first guess.

4.1. Application to the central region of the Iberian peninsula

During the summer months, the meteorological situation at the surface typically observed over the Iberian peninsula is one of a depression or thermal low (Castro, 1989). Although the presence of this thermal depresion is probably the result of various phenomena, the main cause would appear to be the great dryness of the ground in the central and southern regions of the peninsula.

As has been pointed out above, arid soils heat up considerably during the day as a result of the deficit of latent heat flux from the ground, which has to be compensated by an increase in sensible heat flux. Under these circumstances it is reasonable to assume that, in the middle of the day, the vertical thermal gradients existing in the lower atmosphere over this region should be fundamentally superadiabatic in nature.

In order to evaluate the suitability of these modifications to the methods used in calculating vertical exchange in the case of free convection, the results obtained with the one-dimensional model were compared with actual observations made in the centre of the Iberian peninsula. However, it should be taken into account that as a model of these characteristics obviously cannot take into consideration advection or air subsidence, this comparison is purely orientative in nature.

To perform the comparative study, a typical summer's day (14th July, 1987) was considered, in which a thermal low was formed over the centre of the peninsula. The initial conditions used in the simulation with the one-dimensional model corresponded to the data of the radiosonde carried out at midnight at Madrid International Airport. Taking into account the type of terrain existing in the region, the following values, intermediate between urban areas and dry steppe land, were assigned to the parameters, in accordance with Anthes *et al.* (1987):

$$A = .2;\ M = .1;\ g = .88;\ Zo = .5 \text{ m};\ P = 1250 \text{ (S.I.)}$$

After eleven hours of simulation, the results obtained from the model were compared to the data from the radiosonde performed in the same place at 11:00 hours (LST). Figure 7 shows the vertical potential temperature distributions, both actual and modelled using the three methods analyzed for

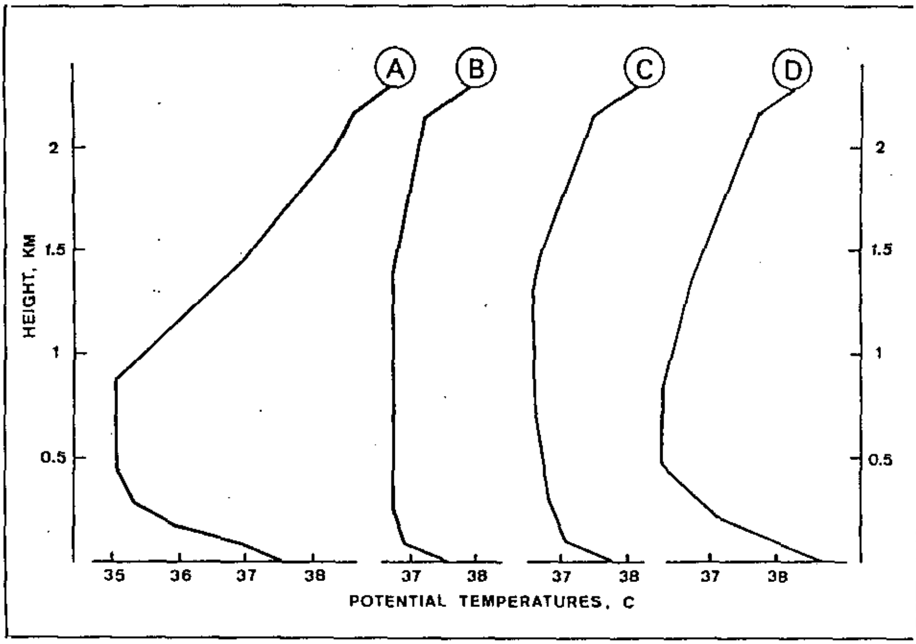

Figure 7.—Potential temperature vertical profiles corresponding to A: 12:00 UT (14-July-87) radiosonde at Madrid. B: Model simulation with constant mixing coefficient *m*. C: Model simulation with variable *m* as suggested by Estoque (1968). D: Model simulation with a dry-convective adjustment scheme.

calculation of vertical PBL exchange. It can be appreciated from the figure that the curve that most closely resembles the real curve is that corresponding to the scheme we have called dry-convective adjustment. In the case of the other two schemes it can be observed that at a few tens of meters height, the potential temperature gradient beccomes nearly zero, which clearly is not the case in reality.

Although, as has been pointed out above, the model used for this simple study would obviously not be the most appropriate for comparing results with reality, it would appear to be the case that in semi-arid areas, such as the centre of the Iberian peninsula in summer, it would be advisable to consider a particular method for more suitable modelling of the intense dry convective phenomena typical of such regions.

5. CONCLUSIONS

When applying three-dimensional prognostic models at beta or gamma mesoscale, special attention should be given to the characteristic and differences of the soils included in the area modelled since, as has been seen, these can have an appreciable influence on the thermal properties and the structure of the lower atmosphere, being capable in some cases of generating local circulations.

Nevertheless, it should be taken into account that each of the soil parameters acts in an appreciably different way. Some have greater influence than others, such that apparently unimportant errors in evaluation of the first might give rise to simulations of the local dynamic atmosphere that are only slightly in keeping with reality.

The results obtained from a simple one-dimensional model of the PBL would appear to suggest the following:

— The avilable moisture of the soil is the most important factor as regards heating of the air adjacent to the ground during the day, as well as regards development of the PBL. Although albedo also influences heating, its effects would appear to be clearly less important than those of soil moisture.
— Roughness affects ground temperature during the day without any effect being observed in the surface layer. This would appear to indicate that this parameter aids latent heat loss from the ground quite efficiently.
— Cooldown of the air adjacent to the ground at night depends fundamentally on thermal inertia and emissivity of the soil, and, to a lesser extent, on the roughness of the terrain.
— In arid or semi-arid terrains and under conditions of dry-convective instability caused by the intense heating experienced in the middle of the day, it would appear to be advisable to consider a specific procedure for modelling the vertical exchange of energy between the layers of air that might allow superadiabatic thermal gradients to be established to heights of several hundred metres above the ground.

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