The radiation and energy budget in mesoscale models: an observational study case

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ABSTRACT:
The radiation and energy budget modelled by means of the mesoscale model MM5 is evaluated against detail surface and upper-air observations. Three consecutive days (24-26th September 2003) were selected for this study characterized by a weak synoptic forcing and by an optimal development of the diurnal variability of surface and boundary layer variables. Particular emphasis is placed to analyze the sensitivity of these budgets to relevant surface properties like albedo and soil moisture availability. The investigation is extended to determine the sensitivity of the main boundary layer characteristics (boundary layer height and mixed-layer temperature) to variations on surface turbulent fluxes due to different surface conditions.
Key words: radiation and energy budget, evaluation mesoscale model MM5.

Balance de Radiación y Energético en los Modelos a Mesoescala: un Caso de Estudio Observacional

RESUMEN:
El balance de radiación y energético calculado con el modelo de mesoescala MM5 es comparado con observaciones recogidas en superficie y de altura. Tres días fueron seleccionados (24-26 Septiembre 2003) en base a una situación sinóptica con poca influencia en la variabilidad diurna de las variables en superficie y en la capa límite. En el análisis de sensibilidad hemos puesto especial énfasis en estudiar los cambios en las variables de radiación y turbulencia a modificaciones del albedo y del contenido de humedad del suelo. La investigación se completa con el estudio de las principales características de la capa límite (altura y temperatura promediada en la capa límite) a las variaciones de los flujos turbulentos de superficie debido a cambios en las condiciones del suelo.
Palabras clave: balance de radiación y energético, evaluación modelo mesoescala MM5.

1. INTRODUCTION

Mesoscale and atmospheric boundary layer (ABL) phenomena are commonly studied separately because of their difference in spatial and temporal scales. However, there is evidence that large scale processes normally classified as mesoscale can exert some influence on boundary layer and surface processes and

vice versa (Jonker *et al.*, 1999). In spite of this evidence and mainly due to computer constraints, relative small scale processes (characterized by smaller spatial scales than the grid cell) like the turbulent fluxes in the boundary layer and surface forcings are represented in a parametric form in mesoscale models. In turn, the increasing possibility to model atmospheric phenomena with finer horizontal resolution (smaller grid cells than 1km) and vertical resolution (~20 m) using mesoscale models has brought the possibility to apply mesoscale models to study characteristic phenomena that occur in the atmospheric boundary layer and its interaction to the land surface. It is therefore very relevant to determine the capability of the boundary layer/surface parameterizations in describing the most relevant processes that occur at the surface and in the ABL. Accurate micrometeorological measurements at the surface combined with upper measurements are therefore an essential evaluating component in assessing the accuracy of numerical models.

In the study described in this paper, we evaluate the radiation and energy budget calculated by means of the mesoscale model MM5 (Dudhia, 1993) with observations taken at Cabauw (the Netherlands) during the 24th, 25th and 26th September 2003. In particular, the 25th September is an optimal day due to the development of a clear convective boundary layer with almost negligible effects of horizontal advection and cloudless skies (Bosveld *et al.*, 2004). The surface and upper air conditions were monitored in detail. Specifically all the components of the radiation and energy budget were measured at the surface. The evolution of the boundary layer height was observed by boundary-layer profile measurements, *i.e.* wind profile/RASS system. These measurements were completed with observations at the Cabauw tower of the thermodynamic variables at six different heights (up to 200 m above ground level).

Previous evaluations studies (Seaman et al. 1989; Berman and Rao 1999; Braun and Tao 2000; Zhong and Fast 2003; Fernández et al. 2007) have investigated whether MM5 was able to simulate successfully the main surface and ABL variables. However, these research studies were carried out under meteorological situations: urban area, coastal and complex orography zones, surface and boundary layer condition in the development of hurricane or climate aspects. Our research extends the previous studies and is focused on critically evaluating the surface budgets, the sensitivity analysis to relevant surface conditions and the implication in the development of the main boundary layer characteristics.

2. BUDGETS AT THE EARTH'S SURFACE: RADIATION AND ENERGY

The physics of the air and land at the atmosphere-biosphere interface are governed by the contributions of short and longwave incoming and outgoing radiation (Garratt, 1992). The intensity of incoming solar radiation at the top of the atmosphere and its transmissivity through the atmosphere determines the shortwave radiation that reaches the surface, i.e. incoming shortwave radiation ($S\downarrow$). Part of this incoming shortwave radiation is reflected upwards by the

surface, namely the outgoing shortwave radiation (S↑). This outgoing shortwave radiation depends on the reflective properties of the surface characterized by the albedo. The albedo is defined as the fraction of downwelling radiation at the surface that is reflected. Its value can vary from 0.05 to 0.9 depending on the properties of the land surface.

In addition, the surface receives another contribution at longer wavelengths due to the emission by the greenhouse gases. This radiation contribution is called the incoming longwave radiation (L↓). The Earth's surface emits back to the atmosphere part of this longwave radiation (outgoing longwave radiation (L↑)). This emission depends on the surface temperature and the surface emissivity (ε) and it follows the Stefan-Boltzman law. If the Earth emitted as a perfect black body and no atmospheric window were considered, ε = 1. However, if one takes into account the atmospheric window the emissivity values can range from 0.9 to 0.99. By adding the incoming and outgoing shortwave and longwave radiation contributions, one obtains the radiation budget at the surface:

$$R_n = S\downarrow + S\uparrow + L\downarrow + L\uparrow, \qquad (1)$$

where R_n is the net radiation at the surface. Notice that in equation (1), S↓ and L↑ have a negative sign.

The conservation of the energy at the interface between the land and the atmosphere requires to establish a relationship between the net radiation and the turbulent fluxes. The net radiation is therefore partitioned into sensible heat flux (H), latent heat flux ($L_v E$) and soil heat flux (G). By so doing, the surface energy balance reads:

$$R_n - G = H + L_v E. \qquad (2)$$

The left hand side of this balance (2) defines the available energy at the surface. A relevant aspect, related to this research, is the calculation of the sensible, latent heat flux and soil heat flux in mesoscale models. The generic forms to represent H, $L_v E$ and G are:

$$H = \rho_a c_p C_\theta V_a (\theta_s - \theta_a) \qquad (3)$$

$$L_v E = \rho_a L_v M C_q V_a (q_{vs}(T_g) - q_{va}) \qquad (4)$$

$$G = 1.18 \Omega C_s (T_g - T_m). \qquad (5)$$

In short, these representations (parameterizations) show that the surface turbulent fluxes are a function of the gradient between the surface temperature (θ_s) (saturated specific humidity at the surface $q_{vs}(T_g)$) and the air temperature at the first-model level (θ_a) (specific humidity (q_{va})), the velocity near the surface, normally associated to the first level (V_a) and a bulk (drag) transfer coefficient (C_θ,

C_q) that relates turbulent fluxes to mean properties of the flow. Notice that these interfacial drag coefficients depend on stability parameters. The air density is ρ_a, the specific heat at constant pressure is c_p and L_v is the latent heat of vaporization. Notice also that in expression (4), the latent heat flux depends on the moisture availability (M) at the surface. In the expression of the soil heat flux, Ω is the Earth's angular velocity, T_g is the absolute ground surface temperature and T_m is the 24-mean absolute temperature at 2 m. More information on the specific expressions of the surface turbulent fluxes and drag coefficients can be found at Braun and Tao (2000) and at Steenveld et al. (2007).

As shown by the radiation budgets (1) and (2), any modifications on the values of the albedo (related to S↑) , the emissivity (related to L↑) or the soil moisture availability (related to the Bowen ratio $=H/L_v E$) will induce a change in several of the terms in each equation. In addition, the evolution of the thermodynamic variables at the surface (θ_g, q_{vs}) and in the first atmospheric level (V_a, θ_a, q_{va}) is fundamental to obtain accurate evolution of the modelled surface turbulent fluxes. Our primary goal is to study the sensitivity of the mesoscale models to variations on surface properties and certain thermodynamic variables.

3. METHODS

3.1. OBSERVATIONS

The Cabauw meteorological tower (height 213 ASL) is situated at the center of the Netherlands (51°58' N), approximately 50 km East of the North Sea and 1 km North West of the River Lek. The Cabauw site lies in an open field nearly completely covered by short grass (Lolium perenne) which extends for several hundreds of meters in all directions. The immediate surroundings of the tower have been described in detail at previous investigations (Van Ulden and Wieringa, 1996; Beljaars and Bosveld, 1997). Pastures exist in all directions within the first hundreds of meters and meadows extend for several kilometers to the West, whereas meadows give way to trees and low buildings on the East. The region surrounding the meteorological tower is rather flat for a distance of at least 20 km, with many fields and scattered canals, villages, orchards and lines of trees. Therefore, the site was chosen due to the representativeness of the surrounding landscape.

The tower was established in 1973 specifically for studying the atmospheric boundary layer. Vertical profiles of wind, temperature, humidity and carbon dioxide are measured along the tower. Measurements for temperature are taken at 2, 10, 20, 40, 80, 140 and 200 m, whereas CO_2 concentration is recorded at 20, 60, 120 and 200 m. Basic meteorological observations include also surface pressure and dew point temperature at the seven mentioned heights. Fluxes of momentum, sensible heat, latent heat and carbon dioxide are measured at 5, 60, 100, 180 m height. Short wave downward and upward is measured as well as long wave downward and upward radiation at the surface. Therefore, the net radiation is explicitly calculated from these radiation fluxes. Radio soundings are performed two times a day at the nearby synoptic station De Bilt (approximately 25 km).

The selected days of this study were characterized by clear skies and an almost negligible contribution of horizontal advection, i.e. classical convective boundary layers are formed Monin-Obukhov length scale is equal to -8 m. The 25th September 2003 is chosen as the most ideal day since the atmospheric boundary layer was mainly governed by the surface fluxes and the heat entrainment at the interface between the ABL and the free troposphere. Advection of heat and moisture was not an important contribution. Briefly, the evolution of the ABL during the day is as follows. A clear distinction between night and day was observed. A stratified shallow stable layer gives place to a convective mixed layer after the morning transition at around 8 UTC. The height of the nocturnal stable layer is estimated to be about 50-100 m. Radiative cooling acts at the surface and consequently a surface inversion layer is formed with colder temperature near the surface. The measured short wave downwards radiation confirms an evolution on time which closely follows a sinusoidal function (see Fig. 1a) and therefore unaffected by the presence of clouds. Measurements from the radiosonde performed at De Bilt at 12 UTC indicate a well mixed layer of about 1200 m for that day. That is in agreement which what is found by analyzing wind profiler measurements for that day.

3.2. NUMERICAL EXPERIMENT SET UP

The radiation and energy budget of the mesoscale model MM5 are studied and evaluated against the Cabauw tower observations. Since, MM5 is a widely used model, we consider that our research provides a first indication of the ability of such models in reproducing these budgets. For the simulation we have defined four nested domains centered at the latitude and longitude coordinates of the Cabauw mast. The following grid lengths were prescribed: 27, 9, 3 and 1 km. Each domain is defined by 31 x 31 grid points. We have prescribed 31 vertical levels in all the domains with higher resolution in the atmospheric boundary layer (almost 15 grid points in the first 1500 meters) in order to describe more adequately the interaction between this layer and the surface layer. Consequently, the first-level model is at approximately 0.5 m and the second one at approximately 10 meter. ECMWF data is used to initialize and update every 6 hours the MM5 boundary conditions. A 24-hour spin-up is applied to allow the parameterizations to adapt to the initial ECMWF conditions.

The physical options used in these numerical experiments were the following. A simple soil model is composed by 4 levels. In selecting this surface scheme to carry out this evaluation study a rather simple land surface scheme, we aim at analyzing the capacity of such schemes to reproduce the radiation and energy budget. We are aware that a more complete scheme can give better results. However, they normally require more information on the surface properties that are often not available. The boundary layer parameterization to calculate the momentum, heat and moisture turbulent fluxes is a first-order scheme. This scheme has the possibility to include in the parameterization the

local approach by prescribing an exchange profile (K) and the non-local approach if the entrainment process is important. It is named the Medium Range Forecast (MRF) (Troen and Mahrt, 1986; Hong and Pan, 1999). A previous study (Vilà-Guerau de Arellano et al., 2001) has indicated that this boundary layer scheme gives better results in representing convective boundary layers than the ones that account only with the local approach. In the coming section, we discuss the results obtained at the smallest domain defined with the finest resolution (1 km x 1 km).

The first run was set to determine if the model could reproduce the main features of Cabauw data. In this experiment, we have kept all the physical options and surface properties as they stand in the MM5 model (version 3.5). We name it 'standard case run'.
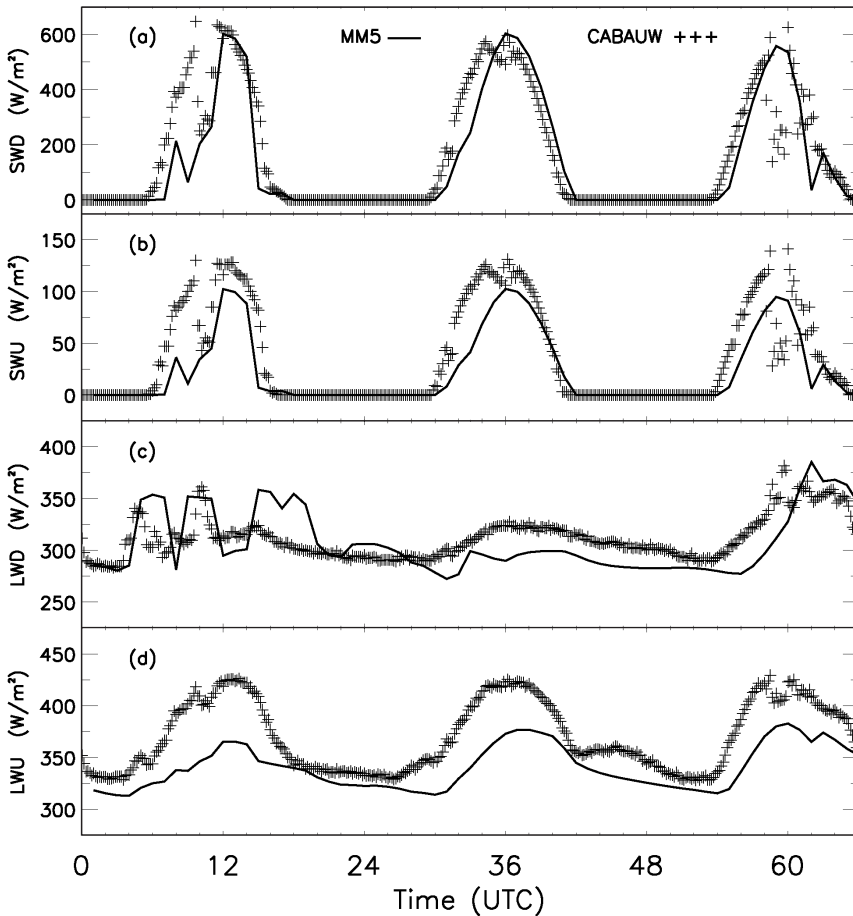
4. RESULTS

First, we present the simulations with the standard options described above. Second, we discuss possible solutions to improve the models results and show the sensitivity analysis to relevant surface conditions.

4.1. RADIATION BUDGET

Figure 1 shows the four components of the radiation budget (eq. 1) during the three days under study. Notice that in the time-axis the time is represented in hours. The 25th September is from 24 to 48 UTC. Model results of the shortwave component agree rather well with observations, with a similar maximum for the incoming shortwave radiation and an underestimation for the outgoing shortwave radiation (approximately 30 W/m^2). The three days show a smooth diurnal variation, except during the 24th September (first analyzed day) where the presence of clouds between 10 and 12 UTC introduce perturbations in the values of $S\downarrow$ and $S\uparrow$.

Figure 1 A characteristic feature observed in the figure for both shortwave components is the shift during the first hours two hours of the morning transition. We have investigated the reasons of this delay in the modelled shortwave component and it can partially be corrected by increasing the frequency of the calculation of the radiation components. We have carried out the same simulation and computed the transfer of radiation in the atmosphere at the following time intervals: every 1 minute, every 30 minutes and every 60 minutes (standard option).

Fig. 2 shows the model results of $S\downarrow$ for the three calculations compared to the measurements for the most optimal day (25 Sept. 2003). Although there is still a delay of approximately 10 minutes at dawn (probably related to the frequency of the output results), the modelled results calculated with the 1-minute frequency are closer to the observed values. In spite of the increase of the computational time, it is therefore recommended to calculate with a high frequency the radiation

Figure 1.- Temporal evolution of the four components of the radiation budget at the surface during the 24, 25 and 26th September 2003. MM5 results are represented by the continuous line and the observational measurements are represented by the cross. For the equivalence with expression (1) the following symbols are used: SWD = S↓; SWU = S↑; LWD = L↓; LWU = L↑.

components. This fact can be particularly important in modelling the morning transition from nocturnal to diurnal conditions.

As shown at figure 1b, the S↑ is mostly slightly underestimated in the three days under study. A series of numerical experiments were done to study the sensitivity of this variable to the albedo. We have kept equal all the other surface conditions and we have varied the value of the albedo from 0.17 to 0.25 of the Cabauw area. Although the model results with higher albedo show an increase of S↑, the improvement compared to the observations is minimal.

The time evolution of the incoming longwave radiation (Fig 1c) follows rather well the nocturnal and diurnal variability of the measurements with a tendency to underestimate. This behaviour is more extreme in the outgoing lonwave radiation
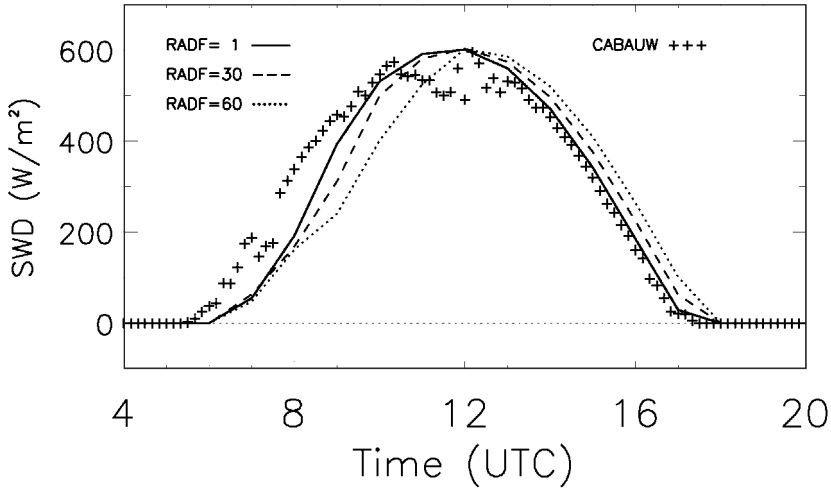
Figure 2.- Model results of the incoming shortwave radiation (25th September 2003) calculated using three different frequencies of the radiative transfer model (RADF): 1-minute, 30-minutes and 60-minutes. The cross indicates the observations.

(Fig 1d) with clear underestimation during the day (approximately 100 W/m^2) and the night (20 W/m^2). The model results are insensitive to modifications of the emissivity parameter. We have modified if from 0.92 to 0.96 without a significant improvement. As mentioned before, the outgoing longwave radiation depends strongly on the temperature near the surface. Fig. 3 shows the comparison of the
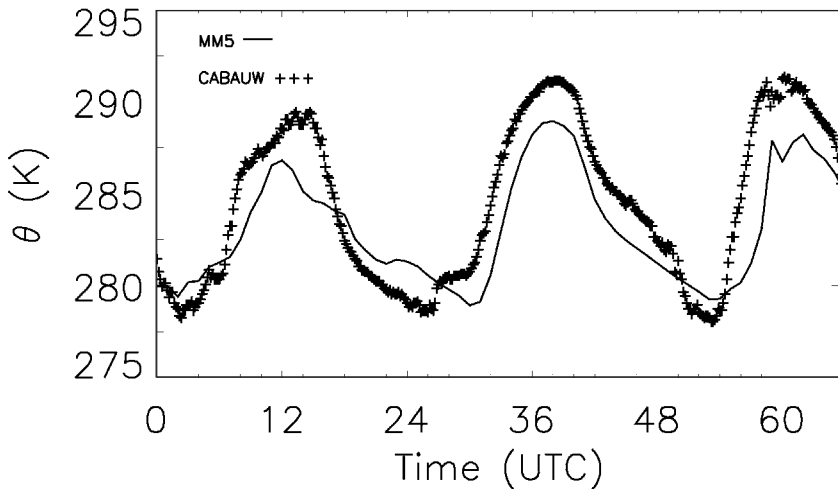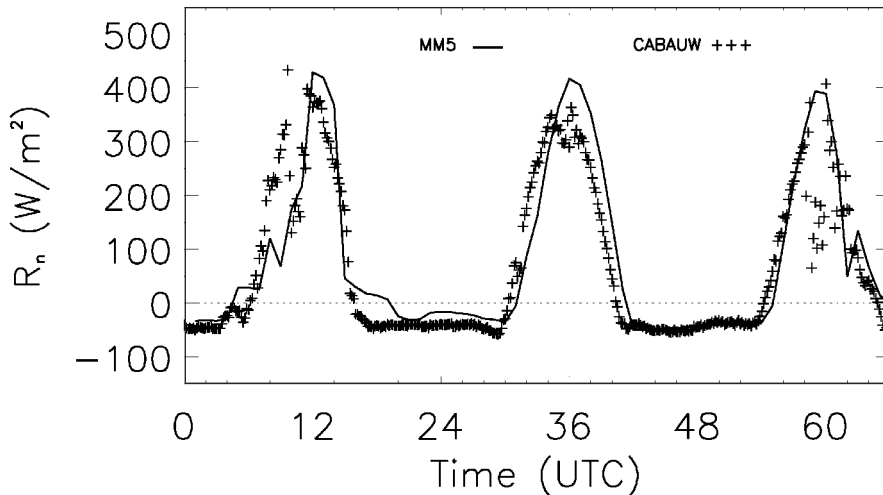

Figure 3.- Measured and modelled air temperature at 2 m during the 24, 25 and 26th September 2003. MM5 results are represented by the continuous line and the observational measurements are represented by the cross.

measured and modelled air temperature at 2 meters. During the day the maximum temperature observed is higher than the model calculations whereas during the night this pattern is reversed.

Steenveld et al (2007) have carried out a recent study investigating possible solutions to improve this temperature calculation near the surface. A large improvement in the calculation of the temperature during nocturnal conditions has been obtained by including a vegetation layer between soil and the atmosphere to mimic an isolating stagnant air layer in the MM5 model. This modification has been introduced in combination with a new expression for the soil heat flux different than (5) and the inclusion of stable-local scaling in the calculation of the turbulent fluxes. Additionally, the investigation also shows the sensitivity of the temperature to the prescribed radiation scheme. A recent model intercomparison with two other mesoscale models (HIRLAM and COAMPS) with detailed observations gathered during the experimental campaign CASES-99 show a large improvement in the MM5 calculation of the temperature at 2 meters.

Although at this point we are still seeking for potential solutions to improve the model calculations of the radiation components, the important variable that has to be accurately modelled is the net radiation R_n. Fig. 4 shows the net radiation for the three consecutive days. In general, the agreement between model results and observations is very satisfactory. For the best analyzed day (25th Sept. 2003), model results are slightly higher near the maximum, but the agreement with the net radiation measurements is very satisfactory. Notice that, as the energy budget indicates, this variable represents the radiation input in the calculations of the turbulent fluxes.
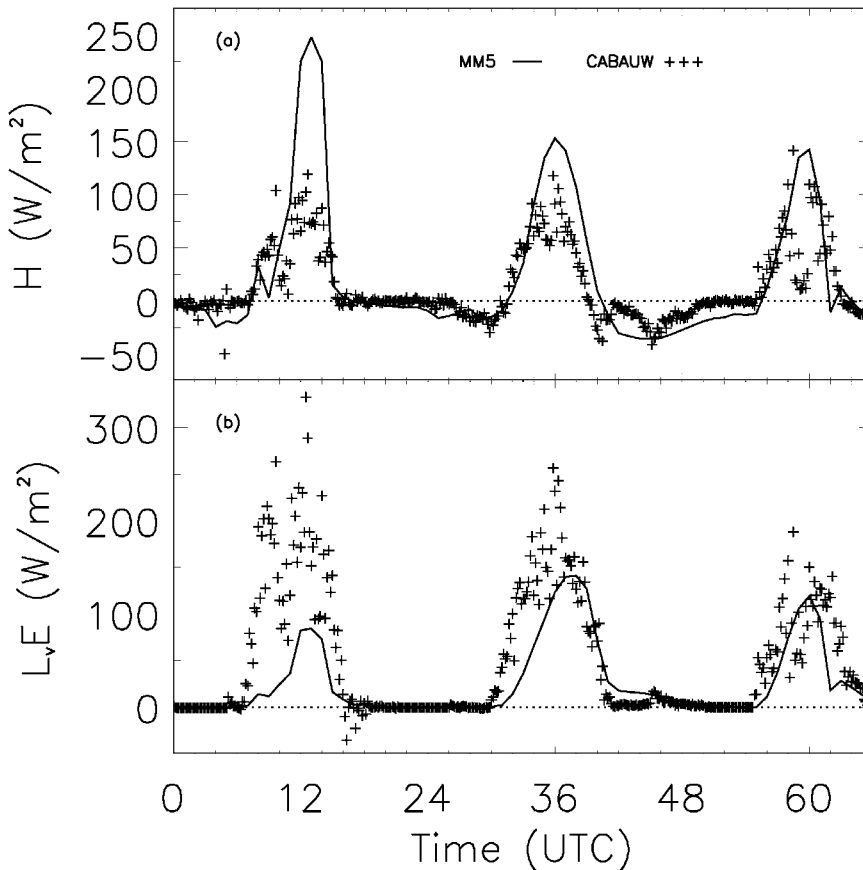

Figure 4.- Temporal evolution of the sensible and latent heat flux at the surface for the 24, 25 and 26th September 2003. MM5 results are represented by the continuous line and the observational measurements are represented by the cross.

4.2. ENERGY BUDGET

The two surface turbulent fluxes (H and L_vE) of the energy budget for the three days under study are shown at Fig. 5. The first 24-hours should be analyzed with cautions since the flux parameterizations of the land surface and boundary layer scheme are adapting to the initial and boundary layer conditions. An overestimation (underestimation) for H (L_vE) is found when comparing the model results with the surface observations. For the latent heat flux, it is also found a delay in the modelled values during the raise of the flux in the morning development of the boundary layer.

Focusing mainly on the best day (25th Sep. 2003), we analyze the sensitivity of the turbulent fluxes to the soil moisture availability (parameter M at eq. 4). At the standard surface land use properties, at Cabauw, the prescribed value of the soil

Figure 5.- Temporal evolution of the net radiation flux (R_n) at the surface during the 24, 25 and 26th September 2003. MM5 results are represented by the continuous line and the observational measurements are represented by the cross.

moisture availability M is equal to 0.3. This value is rather low compared to the normal wet conditions that characterize the soil at Cabauw. As a consequence, we carry out another simulation and increase the value of M to 0.6. Fig. 6 shows the results of the sensitivity analysis study for the sensible heat flux and the latent heat flux. For H, model results reproduce satisfactorily the observations with lower values for the maximum values. Notice, however, that the flux measurements can be 15 % underestimated due to the omission of the low frequencies in calculating the fluxes. By adding this potential bias from the observations, the agreement between model results and observations is improved.

The model values of increased L_vE increase improve the agreement with the observations. Besides, the shift between model results and the observations between 8 and 10 UTC is reduced. These results pointed out the relevance of accurate values of the soil moisture availability in order to model accurate values of the surface turbulent fluxes.
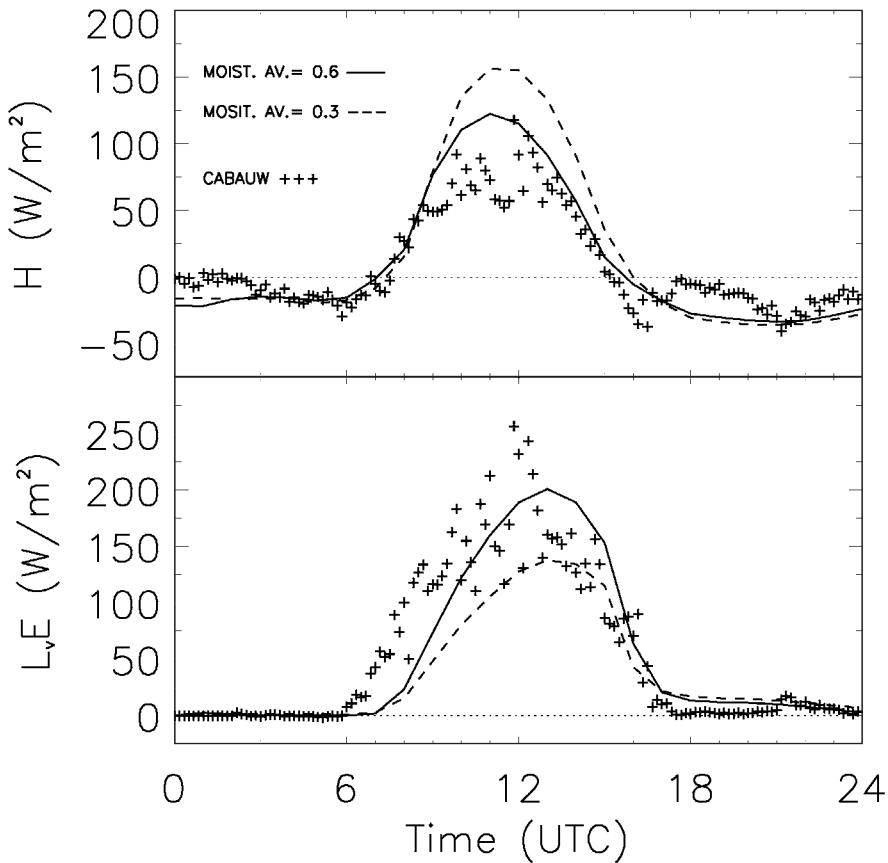
Figure 6.- Sensitivity analysis of the turbulent fluxes to the soil moisture availability: (a) sensible heat flux and (b) latent heat flux.

4.3. IMPLICATIONS TO THE BOUNDARY LAYER MAIN CHARACTERISTICS

Since the total value of the sensible heat flux and the latent heat flux and their partition, the so-called Bowen ratio, have a direct impact on the evolution on the boundary layer characteristics, we decide to perform a sensitivity analysis to determine how variations in the surface turbulent fluxes influence the boundary layer development. In order to simplify the analysis, we carry out the study with a mixed-layer model (Tennekes, 1973) instead of the MM5 model. By so doing, we avoid possible feedback of other processes and facilitate to control the effect of initial and boundary conditions on the model results. Previous studies (Vilà-Guerau de Arellano et al., 2004) have shown that the mixed layer model is able to reproduce accurately the main properties of the development of convective layers similar to the one observed the 25th September 2003. Therefore, this study is also applicable to boundary layer schemes implemented in mesoscale models.

The situation modeled with the mixed layer model is the 25th September 2003. Table 1 shows the initial values prescribed in the model and the surface values. The prescribed surface fluxes follow a sinusoidal with the maximum value indicated at Table 1. Two different experiments were carried out based on the surface fluxes presented at Fig. 6. The first one is characterized by high sensible heat flux and low latent heat flux (Bowen ratio 1.13 based on the maximum values at Table 1) (DRY case). In the second experiment, we have prescribed the surface turbulent fluxes using the values obtained in the MM5 model run using higher soil moisture availability (M=0.6). This case is defined by a lower Bowen ratio (0.6) (WET case). Note that the rest of the initial variables are kept constant.

Table 1.- Initial and prescribed values for the mixed layer model to calculate the boundary layer height, the mixed layer values of the potential temperature and the jump of the potential temperature between the free troposphere and the boundary layer height. Sensitivity analysis is performed to the surface turbulent fluxes (bold variables).

	M = 0.3 (Standard)	M = 0.6
BL height z_o	120 m	120 m
Sensible flux H_{max}	**156 W/m^2**	**120 W/m^2**
MXL pot. temp. θ_o	284.8 K	284.8 K
Jump. $\Delta\theta_o$	2.0 K	2.0 K
Temp. lapse rate Υ_θ	6 K/km	6 K/km
Entr. flux / Surf. flux. ß	0.4	0.4
Latent flux L_vE	**138.6 W/m^2**	**198.9 W/m^2**
MXL spec. humid. q_o	4.5 (g_w/kg_{air})	4.5 (g_w/kg_{air})
Jump spec. hum. Δq_o	-1.0 (g_w/Kg_{air})	-1.0(g_w/kg_{air})/
Spec. hum. lapse rate Δ_q	0 (g_w/kg_{air})/Km	0 (g_w/Kg_{air})/Km
Subsidence velocity w_s	0 m/s	0 m/s

Fig.7 shows the evolution of the boundary layer growth (z_i) in both numerical experiments compared with the observations retrieved from a wind profiler at Cabauw (Klein-Baltink, 1998). The observations of z_i are shown as an indication of the boundary layer growth evolution. The WET case shows a slower growth in better agreement with the observations in the morning evolution (until 12 UTC) and when the boundary layer reaches an steady-state (after 13 UTC). The differences in the absolute values of z_i for both experiments range from less than 100 m in the morning to more than 200 m in the early afternoon. These differences can have an impact on the dilution of atmospheric compounds and the initial formation of boundary layer clouds. For instance, key properties of cloud formation such as the height of the lifting condensation level (LCL) are very sensitive to these variations. In mesoscale models and other large scale models, the saturation processes are only initialized if LCL < z_i. Errors in the calculation of z_i due to uncertainties in surface condition can therefore feedback in other boundary layer processes. (Vila-Guerau de Arellano, 2007).

Figure 7 and Figure 8 shows the time evolution of the potential temperature and the specific humidity for the bulk (mixed-layer) values. Model results are compared with the observed 200-meter value observed at the Cabauw mast. This measurement is the value that represents better the evolution of the mixed-layer thermodynamic characteristics since it is not influenced by the surface fluxes and the strong gradients near the surface. The model has been initialized to match the first observed value that indicates the onset of the convective boundary layer formation (around 8.45 UTC). Fig. 8a shows that the numerical experiment with M=0.6 agrees better with the observations than the one based with surface fluxes using M=0.3. The differences between both experiments are around 1 K once the boundary layer
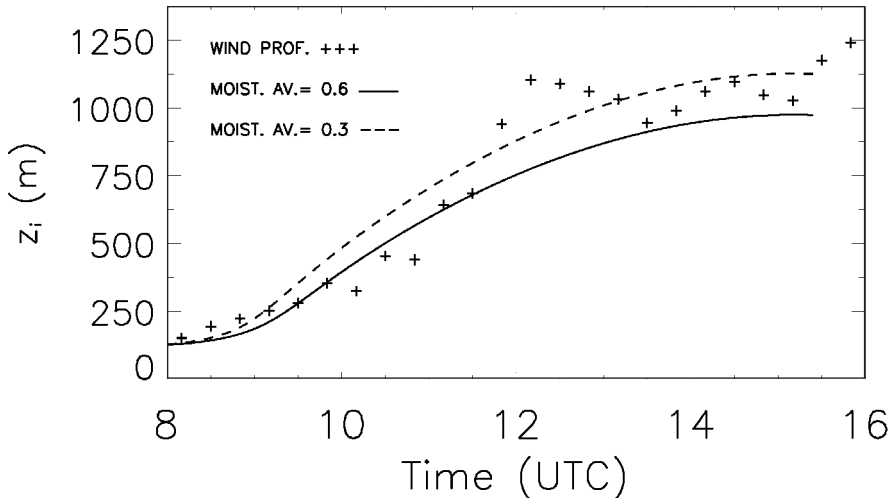
Figure 7.- Time evolution of the boundary layer height calculated by the mixed-layer model using the following values for the soil moisture availability: M=0.6 and M=0.3. The observed values by the wind profiler are also shown.
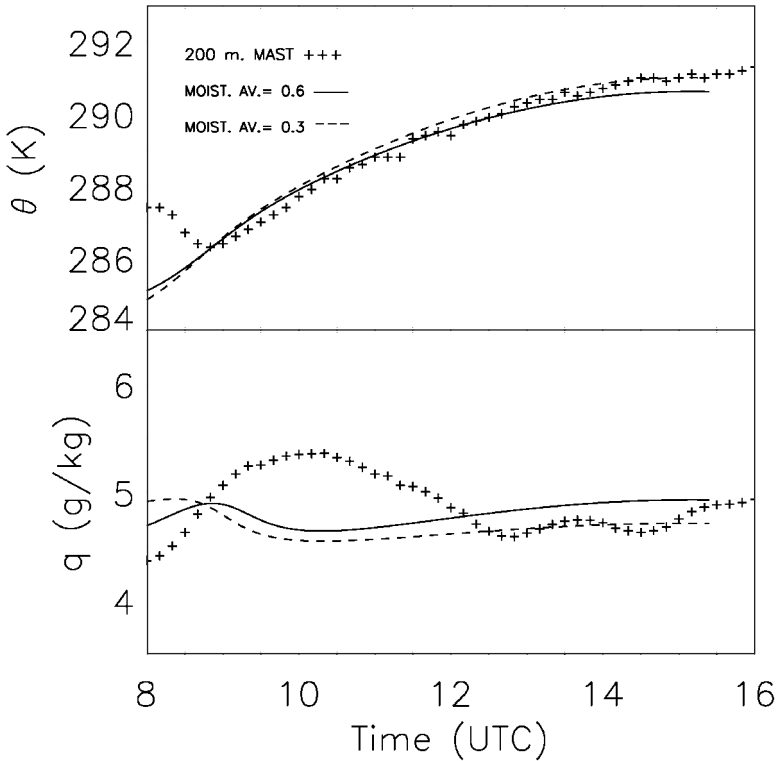
Figure 8.- Time evolution of the (a) potential temperature and (b) specific moisture calculated by the mixed-layer model using the following values for the soil moisture availability: M=0.6 and M=0.3. The observed values at 200-meter at the Cabauw tower are also shown.

reaches an steady-state in the early afternoon. This shows the sensitivity of the maximum temperature to the surface conditions.

Fig 8b shows the evolution of specific moisture. Both numerical experiments, DRY and WET, show large differences compared to the measurements. The morning peak of q, closely associated to the morning transition, is reproduced too early in the mixed layer model compared to the observations. After 12 UTC, the DRY case is in better agreement than the WET case. At this point, it is difficult to give an explanation of these differences between the model and measurements. However, note that in this analysis, we have not taken into account the contribution of advection to the temporal variation of the specific moisture.

5. CONCLUSIONS

Micrometeorological observations at Cabauw (The Netherlands) are used to study the representation of the radiation and energy budget calculated by the mesoscale model MM5. The three selected days were characterized by a weak synoptic forcing,

cloudless and smooth diurnal evolution of surface and boundary layer variables. The model results of the net radiation agree well with the observations, although some of the components of the radiation budget, for instance the outgoing longwave radiation, are very sensitive to the temperature near the surface.

It is found that the surface turbulent fluxes of the energy budget are very sensitive to the soil moisture availability. Once, we are able to adjust this value, the agreement between model results and eddy covariance flux measurements is satisfactory. It is therefore fundamental to have reliable information on surface properties to calculate the absolute values of the sensible heat and latent heat flux. By means of a mixed-layer model, we study how different surface forcing influences the evolution of the boundary layer depth and the mixed-layer values of the potential temperature and specific humidity. It is found that important processes such as boundary layer growth rate and cloud formation are strongly dependent on the partition of the surface turbulent fluxes.

REFERENCES

BELJAARS, A.C. M. & F.C. BOSVELD (1997). Cabauw data for the validation of land surface parameterization schemes. *Journal of Climate* 10, 1172-1193.

BERMAN, S. & J.Y.K.S.T. RAO (1999). Spatial and temporal variation in the mixing depth over the northeastern United States during the summer of 1995. *J. Appl. Meteorol.*, 38, 1661-1673.

BOSVELD F. C., E. VAN MEIJGAARD, E. MOORS & C. WERENER (2004). Interpretation of flux observations along the Cabauw 200 meter meteorological tower. Proceedings *XVI Boundary Layer Turbulence*, American Meteorological Society, Portland, USA.

BRAUN, S.A. & W.K. TAO (2000). Sensitivity of high resolution simulations of hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.*, 128, 3941-3961.

DUDHIA J. (1993). A nonhydroestatic version of the Penn-State-NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, 121, 1493-1513.

FERNÁNDEZ J, J.P. MONTAVEZ, J. SAENZ, J.F. FERNÁNDEZ-ROUCO & E. ZORITA (2007). Sensitivity of the MM5 mesoscale model to physical parameterizations for regional climate models: annual cycle. *J. Geoph. Res.* 112, D04101.

GARRATT J.R. (1992). *The atmospheric boundary layer*. Cambridge University Press, cambridge, United Kingdom, 316 pp.

HONG, S.-Y & H.-L.PAN (1996). Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, 124, 2322-2339.

KLEIN BALTINK H. (1998). A long-term intercomparison of wind profiler/RASS and tower measurements. *Meteorol. Z.,* 7, 271-279. JONKER, H.J.J., P.G

DUYNKERKE & J. W. M. CUIJPERS (1999). Mesoscale fluctuations in scalars generated by boundary layer convection. J. Atmos. Sci. 56, 801-808.

STEENEVELD, G. J., T. MAURITSEN, E.I.F. DE BRUIN , J. VILÀ-GUERAU DE ARELLANO, G. SVENSSON & A.A.M. HOLTSLAG (2007). Evaluation of limited area models for the representation of the diurnal cycle and contrasting nights in CASES99. *J. Appl. Meteorol.* (accepted).

SEAMAN, M.L., F. L. LUDWIG, E.G. DONALL, T.T. WARNER & C. M. BHUMERALKAR (1989). Numerical studies of urban planetary boundary layer structure under realistic synoptic conditions. *J. Appl. Meteorol*., 28, 760-781.

TENNEKES H. (1973). A model for the dynamics of the inversion above the convective boundary layer. *J. Atmos. Sci.* 30, 558-567.

TROEN, I. & L. MAHRT (1986). A simple model for the atmospheric boundary layer: sensitivity to surface evaporation. *Bound-layer Meteorol.,* 37, 129-148.

VAN ULDEN, A. & J. WIERINGA (1996). Atmospheric boundary layer research at Cabauw. *Bound.-layer Meteorolo.* 78, 39-69.

VILÀ-GUERAU DE ARELLANO J., O. S. VELLINGA, A. A. M. HOLTSLAG , F.C. BOSVELD & K. KLEIN BALTINK (2001). Observational evaluation of PBL parameterizations modelled by MM5. Workshop MM5 on *Impact of physical parameterizations on mesoscale mumerical simulations.* Boulder, USA.

VILÀ-GUERAU DE ARELLANO J., B. GIOLI, F. MIGLIETTA, H.J.J. JONKER, H. KLEIN BALTINK, R. W. A. HUTHJES & A. A. M. HOLTSLAG (2004). Entrainment process of carbon dioxide in the atmospheric boundary layer. *J. Geophys. Res.* 109, doi: 10.1029/2004JD004725.

VILÀ-GUERAU DE ARELLANO J., (2007): Role of the nocturnal turbulence and advertion in the formation of shallow cumulus over land. *Quart. J. Roy. Meteor. Soc.* 133, 1615-1627.

ZHONG S. & J. FAST (2003). An evaluation of the MM5, RAMS and Meso-ETA models at subkilometer resolution using VTMX field campaign in the Salt Lake valley. *Mon. Wea. Rev.*, 131, 1301-1322.