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MODELING THE SUMMER DIURNAL CYCLE IN THE SW IBERIA (THE *CICLUS* EXPERIMENT)

Pedro M. M. Soares*
University of Lisbon, Centro de Geofísica, Lisbon, Portugal
ISEL, Department of Civil Engineering, Lisbon, Portugal

Pedro M. A. Miranda
University of Lisbon, Centro de Geofísica, Lisbon, Portugal

J. Teixeira
Naval Research Laboratory, Monterey, USA

A. P. Siebesma
Royal Netherlands Meteorological Institute, The Bilt, The Netherlands

J. P. Ferreira
Instituto de Meteorologia, Lisbon, Portugal

1. INTRODUCTION

The Southern Portuguese coast is a rather interesting case for the study of boundary layer processes. This region has a complex pattern of surface heating, due to the thermal sea/land and lake/land contrasts, orography, and coastal irregularity resulting in different mesoscale circulations interactions (Fig. 1).

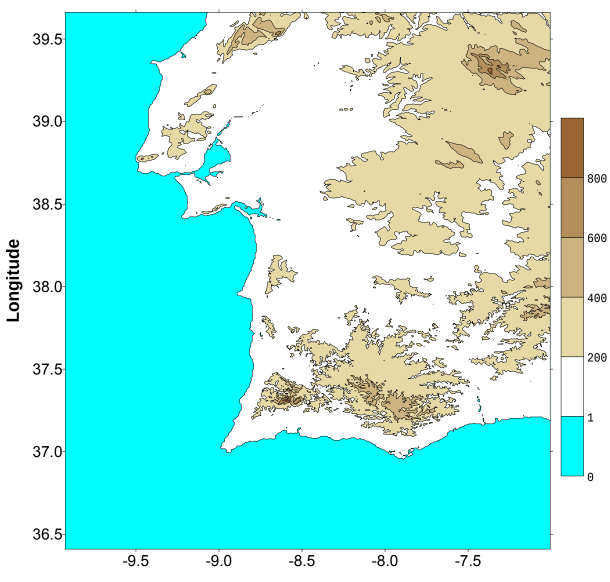

Fig. 1. Southern Portuguese coast and orography.

During the summer, in synoptically non-disturbed days, the regional atmospheric circulation is dominated by a Heat Low type circulation associated with the sea breeze cycle in the Iberian Peninsula. In these conditions the dry boundary layer (BL) is highly turbulent and well mixed, evolving sometimes to a shallow cumulus boundary layer. The sea breeze can penetrate more than 100 km inland (Soares *et al.* 1999), promoting when enough air humidity is presented the occurrence of deep convection by air convergence.

The turbulent mixing in the convective boundary layer is performed by differently sized eddies, ranging from a few millimeters to large thermals with the boundary layer height dimension.

In numerical weather prediction (NWP) models the sub-grid scale vertical transport has to be parameterized. Most Global NWP models still use a first-order closure. In recent years, higher order turbulence closures started to be used on mesoscale NWP models, based on the turbulent kinetic energy (TKE) equation. Both first order and TKE closures are based on the concept of a mixing length, *l*, and require the computation of an eddy-diffusivity, *K*, which in the latter schemes is a function of the TKE. In the eddy-diffusivity approaches, the turbulent flux of a variable ϕ is parameterized by

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z}. \quad (1)$$

The convective BL mean profiles produced by TKE approaches are more realistic, but suffer from some common problems with 1st order closures, namely, an underestimation of top entrainment, and it's intrinsic down gradient character. When moist convection is present in the convective BL, many models use an alternative parameterization for the cloud layer transport, a mass-flux scheme, while the sub-cloud layer is still parametrized by eddy-diffusivity. This discontinuity in the models may contribute to the poor results obtained in the cumulus topped BL (Lenderink *et al.* 2004).

Recently, two different parameterizations based on the prognostic equation of TKE were proposed, to overcome the above mentioned problems.

* *Corresponding author address*: Pedro M. M. Soares, Centro de Geofísica, University of Lisbon, Ed. C8 (3.26), Campo Grande, 1749-016 Lisboa, Portugal. pmsoares@fc.ul.pt

Teixeira and Cheinet (2004) presented a simple mixing length formulation for the eddy-diffusivity parameterization of dry convection. This new formulation relates the mixing length (*l*) to the square root of the turbulent kinetic energy (*e*) and a time-scale (τ), $l = \tau\sqrt{e}$. This approach is able to realistically represent the top-entrainment, but unable to parameterize counter-gradient fluxes, because of it's intrinsic down gradient character. This formulation has been generalized successfully for cloud-topped boundary layers, both in stratocumulus and cumulus cases (Cheinet and Teixeira 2003). In this paper we test this new mixing length formulation using the US Navy coupled ocean-atmosphere mesoscale prediction system (COAMPS^{TM}).

Soares *et al.* (2004) proposed a way of unifying the parameterization of the convective BL, by combining eddy-diffusivity and mass-flux approaches, based on the TKE budget equation. The eddy-diffusivity/mass-flux (EDMF) approach is supported by the concept that small eddies perform local mixing that is parametrized by diffusion, while the non-local mixing due to thermals is represented by the mass-flux term. Accordingly, the turbulent flux is represented by,

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z} + M(\phi_u - \overline{\phi}), \qquad (2)$$

where *u* refers to the strong updraught and a_u is the fractional area of the ensemble of updraughts. The two terms on the r.h.s. of (2) represent, respectively, the eddy-diffusivity and mass-flux contributions, where $M = a_u w_u$ is the mass-flux associated to the ensemble of updraughts. Both contributions are linked to the TKE budget equation. So, the EDMF scheme uses a 1.5 order turbulence closure, but includes a non-local mixing effect, representing the effect of strong updrafts in the BL. These are modeled by a simple entraining rising parcel, and the mass-flux coefficient is proportional to the diagnosed variance of the vertical velocity. The EDMF parameterization is implemented in the research model MesoNH (Lafore *et al.* 1996) taking advantage of the eddy-diffusivity closure of Cuxart *et al.* (2000).

The main goal of this study is to show how the new schemes perform in the simulation of a diurnal cycle of the dry convective BL, in Southern Portugal. An improved representation of the convection will allow a better understanding of the complex interactions that are present, namely the interaction between boundary layer convection and thermally driven circulations, because both can provide favourable regions for cloud development and precipitation. For this purpose, a number of numerical simulations of a diurnal cycle of the convective BL were performed, using the COAMPS and MesoNH models.

The Section 2 of this paper presents the *CICLUS* field campaign and some of the main observations that constitutes the case of a diurnal cycle of the convective BL. The results of the COAMPS model and of the MesoNH model are presented in the Section 3. The main conclusions are presented in section 4.

2. The *CICLUS* field experiment

Between October 1997 and October 1999, a field experiment was performed to better characterise the atmospheric circulations in the South of Portugal (CICLUS - Climate Impact of Changes in Land Use - experiment). The field campaign included two years of continuous surface observations in 37 automatic weather stations; 21 of them, yielded by the Portuguese Met office, are distributed in the region of the Fig. 1, and 16 were installed at the Dejebe basin (approximately 6400 km^2). Between 16 and 31 July 1998, an intensive observation period was performed in this basin, consisting of radiosondes (at latitude 38.53 N and longitude 7.88 W), some tethered balloon ascents, continuous sodar operation, and near surface turbulence measurements with an ultra-sound turbulence sensor (eddy correlation system).

On 24 and 25 July 1998, two days with clear-sky situation, radiosonde observations were performed every 3 hours, providing a detailed picture of the inland boundary layer evolution. In Figures 2 to 5 the observed

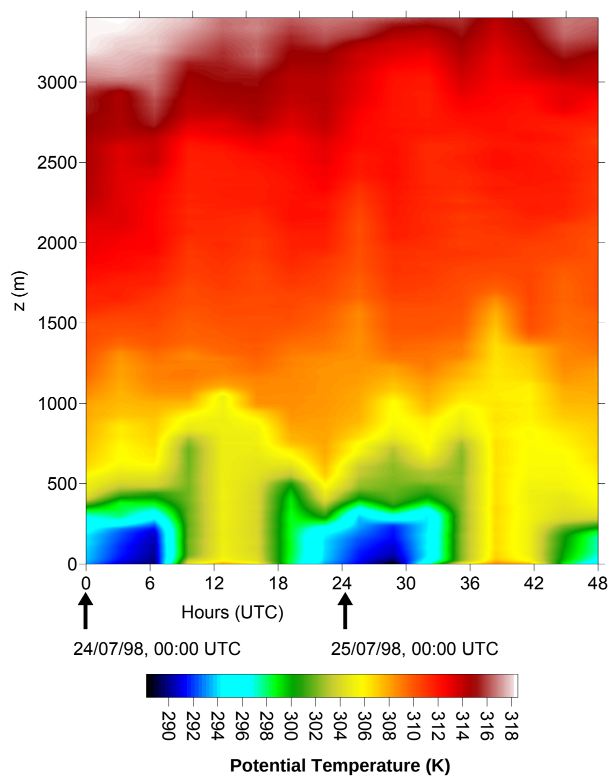

Fig. 2. Time evolution of the potential temperature vertical profiles.

time evolution of the vertical profiles of, potential temperature, specific humidity, zonal wind component and meridional wind component, are shown, respectively. As expected, the PBL height increases throughout the day, reaching its maximum at approximately 15 UTC. During this time, the PBL develops from a stable boundary layer into a well-mixed PBL, toped by a sharp inversion, typical of dry convective situations. The shallow dry layer at around 1000 m height includes air that is advected horizontally south-westwards from the interior of Spain. Above it, lies a layer of moister air of Atlantic origin, in a flow with a clear westerly component. The implied vertical shear is associated with a transition from the cyclonic heat low near the surface and the anticyclonic flow aloft.

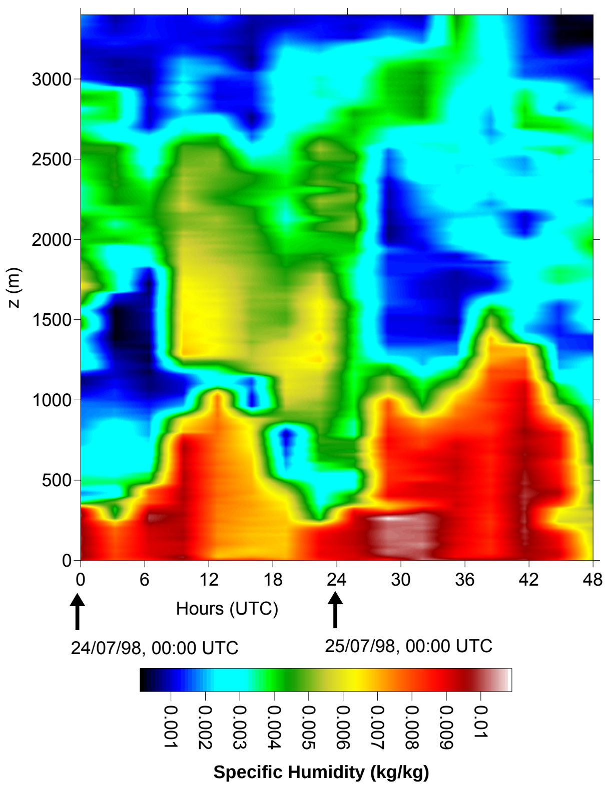

Fig. 3. Time evolution of the specific humidity vertical profiles.

In the second day, 25th July, the diurnal cycle presents the same overall features, but due the residual mixed layer of the day before, the PBL becomes deeper, reaching a maximum height of around 1600m at 15 UTC.

The atmospheric boundary layer circulation in the Lisbon area (at latitude 38.77 N and longitude 9.15 W) is characterized by a complex system of surface heating contrasts. These induce multiple local circulations, the sea breeze, the lake breeze, the Lisbon heat island effect, the Sintra and Arrábida mountains circulations and the convergence and divergence caused by the local coast irregularity.

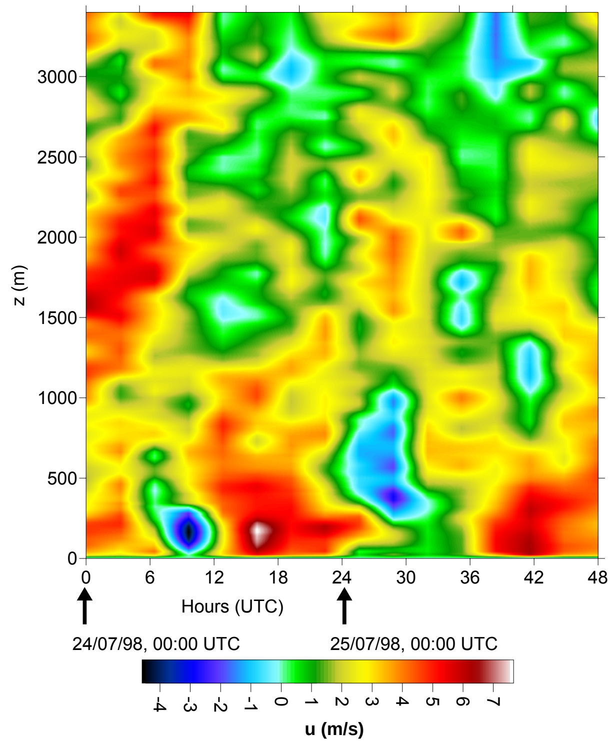

Fig. 4. Time evolution of the zonal wind component vertical profiles.

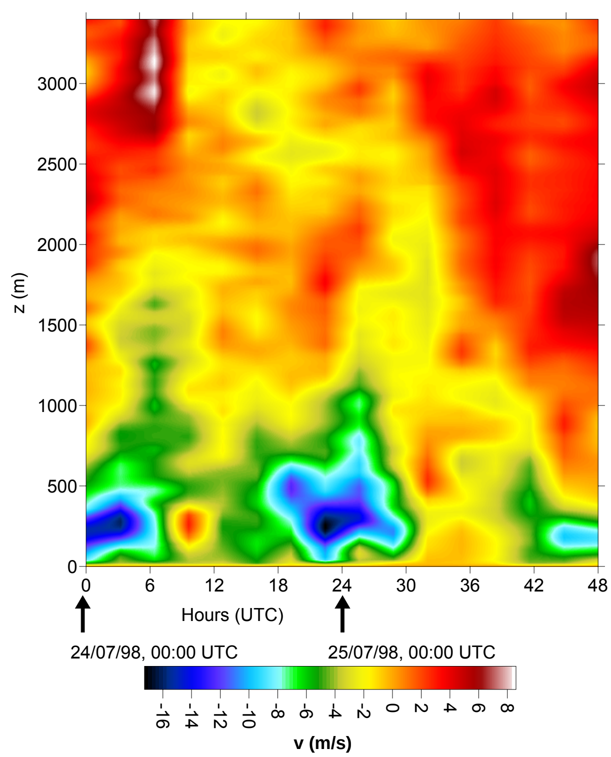

Fig. 5. Time evolution of the meridional wind component vertical profiles.

Soares *et al.* (1999) performed a set of numerical simulations with the mesoscale model NH3D (Miranda and James 1992) coupled with the soil model ISBA (Interactions between Soil Biosphere Atmosphere), developed by Noilhan e Planton (1989), to study the complex atmospheric interactions in the Lisbon region. Their results showed the appearance of an early morning sea and lake breeze, and above the lake it could be seen the divergent flow, result of the two shore circulations. In the following hours the sea breeze propagates inland and its intensity increases, suppressing the lake breeze. The sea breeze maximum intensity is ~ 6 m/s. The lake divergence results in overlying subsidence drying the over lake atmosphere, and forcing the cumulus clouds clearing above and downwind the lake (Fig. 6).

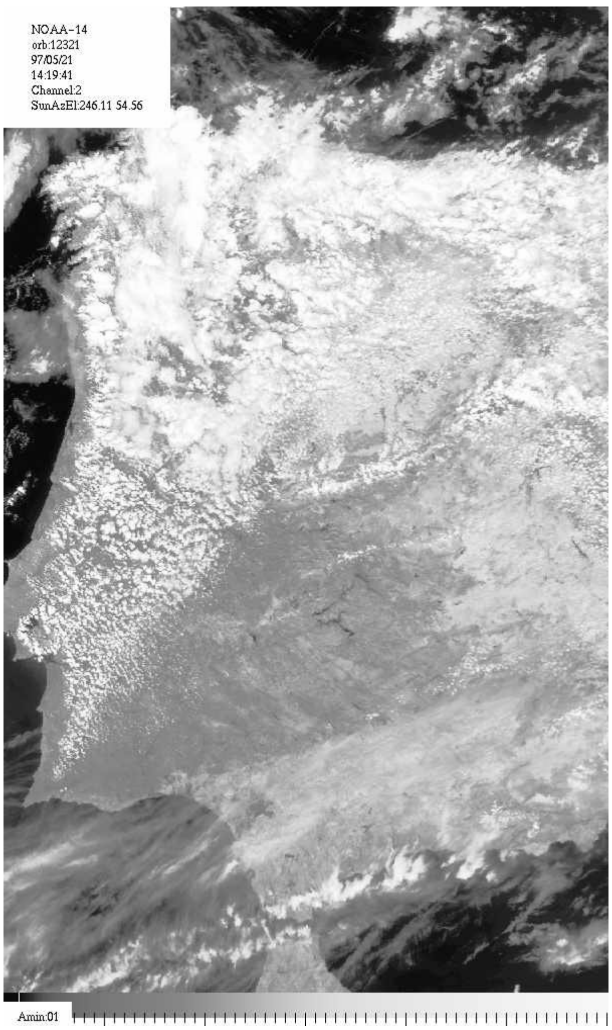

Fig. 6. Visible satellite image (NOAA) of the Iberian Peninsula, showing organized convection, and the cumulus clouds clearing above and downwind the lake.

3. MODEL RESULTS

3.1. *COAMPS*

COAMPS (Hodur 1997; Hodur and Doyle 1998) is a mesoscale model with a finite-difference approximation to the fully compressible, non-hydrostatic equations. COAMPS can be used as an analysis-nowcast and short-term forecast (up to 72 hours) tool, applicable for any given region on Earth. COAMPS includes a full atmospheric data assimilation system with data quality control, analysis, initialization, and non-hydrostatic atmospheric model components, coupled with a hydrostatic ocean circulation model. COAMPS uses a terrain-following vertical coordinate and can be integrated on a system of nested grids that enables the highest resolution to be focused over a specific region of interest.

The BL and turbulence parameterization uses a prognostic equation for the turbulent kinetic energy (TKE) based on Mellor and Yamada (1982). The surface fluxes are computed based on Louis *et al.* (1982) and the radiation parameterization follows Harshvardhan *et al.* (1987). The moist convection processes are parameterized following the approach of Kain and Fritsch (1993) and the cloud microphysics processes are parameterized based on Rutledge and Hobbs (1983). The boundary conditions are from the navy operational global atmospheric prediction system (NOGAPS). The dynamics and numerics of NOGAPS are described in Hogan and Rosmond (1991) and the main physical parameterizations are described in Louis *et al.* (1982), Harshvardhan *et al.* (1987), Teixeira and Hogan (2002), and Emanuel and Zivkovic-Rothman (1999).

The boundary layer parameterization in COAMPS is based on the eddy-diffusivity closure with a prognostic equation for TKE. The eddy-diffusivity coefficients are parameterized as, $K_\theta = K_q = S_{\theta,q} l_h \sqrt{e}$, where θ is the potential temperature, *e* is the TKE, *q* is the water vapor mixing ratio, l_h is the mixing length for potential temperature and water vapor. In the control version of COAMPS $S_{\theta,q,m}$ are functions of the Richardson number (Chen *et al.* 2003), S_e is a constant and the different mixing lengths are equal to a master length scale *l*, calculated using Blackadar's formulation (Blackadar 1962).

As mentioned above the Teixeira and Cheinet (2004) scheme was recently implemented in the COAMPS model (Teixeira *et al.*,2004). For convective situations (positive surface buoyancy flux) we use in this study a constant time-scale equal to 600s. For stable situations we combine Teixeira and Cheinet (2004) with Deardorff (1976) by determining the time scale as $\tau = \min(600, 0.76/N)$ where *N* is the Brunt-Vaisala frequency. For a detailed description see Teixeira *et al.* (2004).

For this particular simulation, the atmospheric component of the COAMPS model was configured in a three-dimensional mode over an area around point

[38.53 N, 7.88 W] in a Lambert conformal projection with the standard parallels being 30° and 45° N. In this application COAMPS uses 30 vertical levels and 3 horizontal domains. The outer grid has 45 km horizontal resolution and uses 45 grid points in each horizontal direction. Nest 1 has 15 km resolution with 49×49 grid points. Nest 2 has 5 km resolution with 85×85 grid points in both horizontal directions. The initial and boundary conditions for the simulation are taken from NOGAPS. Two 24 hour COAMPS forecasts were produced starting from July 24th 1998 at 00 UTC: (i) a control version (CTRL) with the standard mixing length and (ii) a new version (NEW) with the new mixing length formulation. The observations were taken at latitude 38.53 N and longitude 7.88 W, and the COAMPS model results were obtained in the nearest grid point, at latitude 38.529 N and longitude 7.904 W.

Figure 7 shows the potential temperature from the observations and the two model versions at 15 UTC. It is clear that for this situation the current COAMPS parameterization is unable to realistically represent the boundary layer height and mean potential temperature. The control experiment is almost two degrees too cold compared to the observations, and the PBL height is around 500 to 600 m, which is about half of the observed height. With the new formulation the simulation is much improved. Both the mean PBL potential temperature and the PBL height are very close to the observations, showing that the new mixing length formulation is able to produce a realistic entrainment and PBL growth.

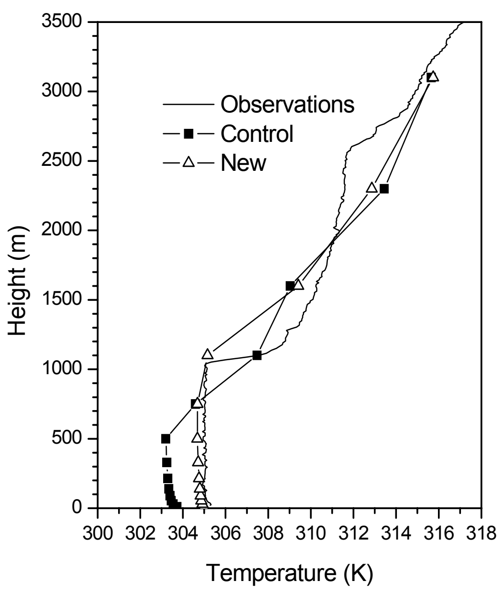

Fig. 7 Profiles of potential temperature (K) at 15UTC, from the observations, the current COAMPS parameterization (control) and the new scheme (new).

In fig. 8, the same is shown but for the water vapor mixing ratio. Again the control version produces a PBL that is not realistic. The model PBL top is too low, leading to a value of the water vapor mixing ratio that is about 4 g kg^{-1} too high. The new formulation leads to values of the mixing ratio that are quite close to the observations. Notice that none of the COAMPS versions seems to be able to capture the large-scale dynamics associated with the moisture minimum around 1000 m. This may well be due to a lack of vertical resolution in order to resolve this type of features.

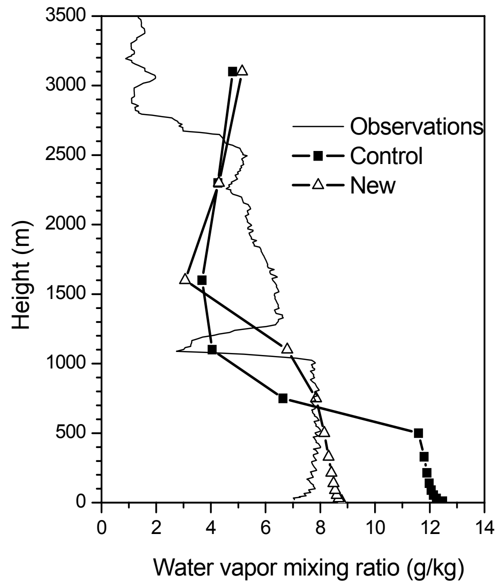

Fig. 8. Profiles of water vapor mixing ratio (gkg^{-1}) at parameterization (control) and the new scheme (new 15UTC, from the observations, the current COAMPS).

Fig. 9 shows a cross-section of the water vapor mixing ratio at latitude 38.529 N, for the control simulation at 15 UTC. This cross section starts offshore in the west and crosses the south of Portugal and Spain, showing a deeper boundary layer over land. Figure 10 shows the differences in water vapor mixing ratio between the new and control experiments. As expected, the new formulation produces deeper boundary layers, leading to higher values of the mixing ratio closer to the top (above the control PBL height) and lower values closer to the surface, due to a more realistic vertical redistribution of the water vapor mixing ratio.

3.2. *MesoNH results*

The MesoNH model has the ability to run both large-eddy and mesoscale simulations. The model uses an anelastic system of equations written with a Gal-Chen and Sommerville (1975) vertical system of coordinates. The MesoNH model has a convection scheme based on the Kain and Fritsch (1993) bulk mass-flux convection parametrization for deep and shallow convection (Bechtold *et al.* 2001).

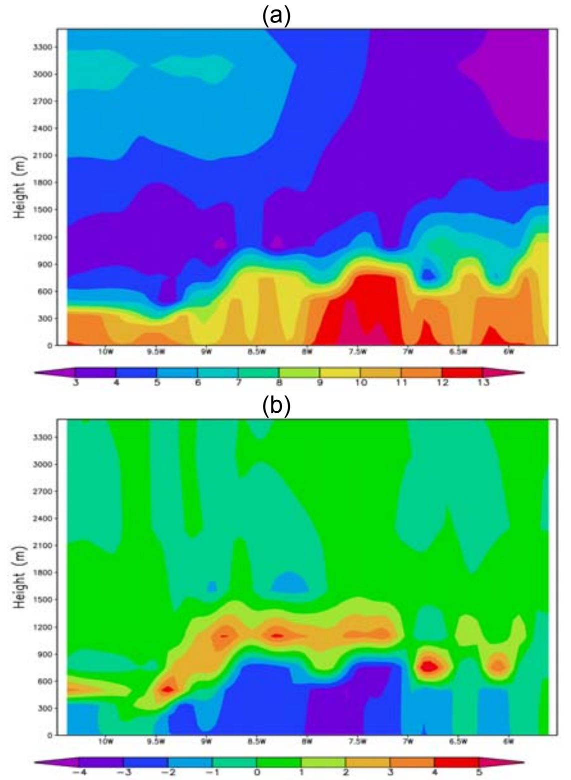

Fig. 9. Cross-section at latitude 38.53° N and at 15 UTC of the water vapor mixing ratio (gkg^{-1}) of (a) the control simulation and (b) the differences between the new and the control versions of COAMPS.

The EDMF scheme implemented in the MesoNH model is able to well represent the diurnal cycle, of both the dry and the shallow cumulus BL (Soares *et al.* 2004). The top-entrainment across the inversion, responsible for the deepening of the BL, during the day, is predominantly represented by the mass-flux term of (2). This term is responsible by the counter-gradient mixing, associated to the convective plumes that dominate the transport in the BL.

The EDMF results in the case, here considered, of the July 24th are similar to the ones produced by the new COAMPS version. Both the mean properties and the BL height are well reproduced by the scheme (not shown).

4. CONCLUSIONS

The mixing length formulation for the eddy-diffusivity parameterization was tested in COAMPS, in the simulation of a dry convective boundary layer observed during a field experiment in Portugal. The current COAMPS formulation produces boundary layers that are too shallow due to a lack of entrainment. As a consequence, the PBL is too cold and moist when compared to the observations. The new formulation directly relates the mixing length to a time scale and the square root of the turbulent kinetic energy. This formulation, previously found to compare well with large eddy simulation model results, dramatically improves the simulation of the dry convective boundary layer in COAMPS. The evolution of the vertical profiles of both potential temperature and water vapor mixing ratio is much more realistic, with the new formulation producing boundary layers that are deeper, warmer and dryer than the current formulation. This implies a better representation of the dry boundary layer development process in general and of the top entrainment in particular.

With the EDMF scheme the clear CBL is also well represented, with a good prediction of both the time evolution and vertical development of the mixed layer. The improved behaviour of the CBL structure is associated with a better representation of counter-gradient fluxes and top entrainment, including the effect of thermal's overshooting. In the upper half of the CBL the non-local mass-flux term dominates over the eddy-diffusivity contribution, allowing for a realistic slightly stable CBL. This is impossible to attain in a pure eddy-diffusivity scheme.

Both schemes present a more realistic simulation of the dry and shallow convective PBL, which will also create better conditions for good forecasts of the onset of deep convection.

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