Turbulent kinetic energy climatology for present and future climate conditions over the Iberian Peninsula as obtained from a TKE closure scheme in a regional climate model

Enrique SÁNCHEZ[1], Carlos YAGÜE[2] and Miguel Angel GAERTNER[1]

[1] Facultad de Ciencias del Medio Ambiente, Universidad de Castilla-La Mancha (UCLM),
Toledo, Spain. (e.sanchez@uclm.es)

[2] Dept. Geofísica y Meteorología, CC Físicas, Universidad Complutense de Madrid (UCM),
Madrid, Spain. (carlos@fis.ucm.es)

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ABSTRACT:
Two 30-year periods, present (1961-1990) and future (2071-2100) climatic conditions under A2-SRES increased greenhouse gases conditions over mosf of Europe and Northern Africa have been simulated with PROMES regional climate model. This model uses a 1.5 order closure turbulent scheme, providing then turbulent kinetic energy (TKE) as a prognostic variable. The analysis of the obtained TKE at climatic scales provides additional information about climatic change processes than just the surface variables analysis, more commonly used for climate change studies. It also gives an original perspective for numerical modelling of turbulent planetary boundary layer description, typically focused on much smaller time and spatial scales. The analysis is here focused over the Iberian Peninsula, as it shows some aspects of interest when dealing with climatic change studies over Europe: it is one of the regions that is expected to present a higher temperature increase, specially for summer season, and also can suffer an important hydrological stress.

Key words: Turbulent kinetic energy, Regional climate model, Climatic change.

Climatología de la Energía Cinética Turbulenta para Clima presente y Futuro sobre la Península Ibérica Obtenidos con un Esquema de Cierre con TKE en un Modelo Regional de Clima

RESUMEN:
Dos períodos de 30 años, clima presente (1961-1990) y condiciones climáticas futuras (2071-2100) para el escenario de emisiones de gases invernadero A2-SRES sobre la mayor parte de Europa y el Norte de África han sido simuladas con el modelo regional de clima PROMES. Este modelo emplea un esquema de cierre turbulento de orden 1.5, con la energía cinética turbulenta (TKE) como variable de pronóstico. El análisis de la TKE obtenida en escalas climáticas proporciona una información adicional sobre procesos de cambio climático frente al análisis de variables de superficie únicamente, más habitualmente usado en estudios de cambio climático. También ofrece una perspectiva original de la descripción de la modelización numérica de la capa límite planetaria turbulenta, típicamente concentrada en escalas espaciales y temporales más pequeñas. El análisis está enfocado sobre la Península Ibérica, pues muestra aspectos de interés específico en relación con los estudios de cambio climático en Europa: es una de las regiones en las que se prevé un mayor incremento de temperatura, especialmente en verano, y también sufre un importante estrés hídrico.

Palabras clave: modelización climática regional, turbulencia, cambio climático.

1. INTRODUCTION

Regional climate models (RCM) have become a very common and useful tool for climate change studies during the last years (Giorgi et al. 2004). In fact, 2007 IPCC WG1 report includes one chapter with a very complete analysis of RCM over many regions around the world (Christensen et al. 2007a). These models typically present a horizontal resolution around 50 km size, compared with the 200 km or more of global climate models (GCM). This increased resolution over a smaller domain allows an improvement in the representation of several atmospheric processes, such as convection, land-surface interactions or orographic mechanisms. From a more wide perspective, it is likely that extreme events can be better described with RCMs, which can be of high importance in relation with climate change studies (Beniston et al. 2007). At the same time, both GCM and RCM models present usually first order closures for their planetary boundary layer (PBL) schemes, and here we will show the results of a 1.5 order closure turbulent scheme.

In the frame of PRUDENCE project (Christensen et al. 2007b), devoted to regional climate simulations over Europe, PROMES-RCM model (Castro et al. 1993) has simulated present and future climates over most of Europe with a 1.5 order closure PBL scheme (Sánchez et al. 2007a, Sánchez et al. 2007b). A detailed analysis of how PBL is described with this model on both climatic periods presents then several aspects of interest. First, it analyzes how PBL is described from a regional climate model with 50 km resolution for a whole climate period. Although PBL time and spatial scales are much smaller than the ones presented here, boundary layer scheme is an important part of the regional climate model, as it describes how surface energy, mass and momentum are vertically transported to the free atmosphere, which is of high importance on any atmospheric analysis (Oke 1988). Not many studies have been made from this perspective, so it can be very interesting to inspect the structure of PBL on these scales. Secondly, it extends the typical climate change studies from just surface variables to the behaviour of the whole planetary boundary layer. Undoubtedly, it will show many aspects in common with surface air temperature analysis (Giorgi et al. 2004, Räisänen et al. 2004, Sánchez et al. 2004, Christensen and Christensen 2007), but at the same time, it will also describe processes covering a wider vertical region than just the behaviour of the atmosphere at the surface. And third, for these analysis, it uses the availability of the turbulent kinetic energy (TKE) obtained here as a prognostic variable, not just a pure diagnostic as it would be from first order closure schemes. TKE is itself a very interesting magnitude to describe PBL processes, as it includes the main energetic mechanisms responsible of turbulence generation, transport and dissipation. Nevertheless, it must not be forgotten the limitations of a RCM to describe the vertical structure of the PBL, when compared with the Large Eddy Simulations (LES) with much higher resolution (Lenderink and Holtslag 2000). The availability of TKE can be then a step forward compared with the first order closure analysis (Shafran et al. 2000; Berg and Zhong 2005).

2. METHODOLOGY AND RCM DESCRIPTION

The RCM used in this study is a state-of-the-art primitive equation model, hydrostatic and fully compressible. Vertical coordinates are pressure-based sigma 28 levels, with the first 8 typically below 1000 m. In the horizontal, a Lambert conformal projection is used, centered on 6ºE-45ºN, and an Arakawa-C grid is used to stagger variables. With 113x97 horizontal points of 50x50 km^2 resolution, the full domain covers most of the European region (except northern Scandinavian Peninsula) and Northern Africa, being its west limit well inside Atlantic Ocean (see Figure 1). The PROMES model uses a split-explicit integration scheme, and all principal physical processes (radiation, large-scale clouds and precipitation, convective processes, land-surface processes, etc.) are included through different parameterizations (Arribas et al. 2003). Two RCM numerical experiments have been simulated: present climate (1961-1990) conditions (named control or CT simulation hereafter), and future (2071-2100) period, with the IPCC A2-SRES scenario described in Nakicenovic and Swart (2000), related to a high increases of greenhouse gases (A2 hereafter). Both periods are forced on domain boundaries every 6 hours with atmospheric HadAM3-GCM model (Pope et al. 2000), where sea surface temperatures (SST) are obtained from observations for present climate (Rayner et al. 2003), and for future period, an anomaly to those SSTs are added, as obtained from the coupled HadCM3 model simulations for both periods (Rowell 2005). The turbulence scheme used in the RCM is a 1.5 order closure scheme, with a prognostic equation for the turbulent kinetic energy (TKE or $\bar{e}$, being $\bar{e} = 0.5\,(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$, where overbars denote ensembled means and u', v', w' the turbulent components of the wind flow), as described in Cuxart et al. (2000).

TKE evolution is obtained from the following equation:

$$\frac{\partial \bar{e}}{\partial t} + u_j \frac{\partial \bar{e}}{\partial x_j} = \overline{u'_i u'_j}\,\frac{\partial \bar{u}_i}{\partial x_j} + \delta_{i3}\,\frac{g}{\bar{\theta}_v}\,\overline{u'_i \theta'_v} + \frac{\partial \overline{u'_j e}}{\partial x_j} + \frac{\partial \overline{u'_j p}}{\partial x_j} - \varepsilon \qquad (1)$$

where u_i denote velocities in each direction, δ_{i3} Kronecker delta, g gravity acceleration, θ_v virtual potential temperature, p pressure, and ε denotes a dissipation term. This equation expresses TKE evolution as a function, on the right side, of their sources and sinks (shear and buoyancy: first two terms), transport (third and fourth terms), and their sink on smaller scales through dissipation mechanisms (fifth term). Closure of turbulent fluxes and dissipation are expressed as a function of a master mixing length L (Bougeault and Lacarrere 1989) ,a magnitude proportional to the bigger eddies associated with turbulence generation and dependent on stability (Redelsperger and Sommeria (1981) proposal is considered).

3. RESULTS

Before a detailed analysis of boundary layer characteristics is shown, main present climatic features of PROMES-RCM model used here were compared against other similar RCMs (Jacob et al. 2007) and observations (CRU database, New et al. 1999) with successful results. This previous analysis give us confidence about the following analysis of their simulated boundary layer characteristics.

For a first global overview of boundary layer energetics, for each point of the domain, vertically integrated TKE values (TKEZ) have been computed for present and future climate period.

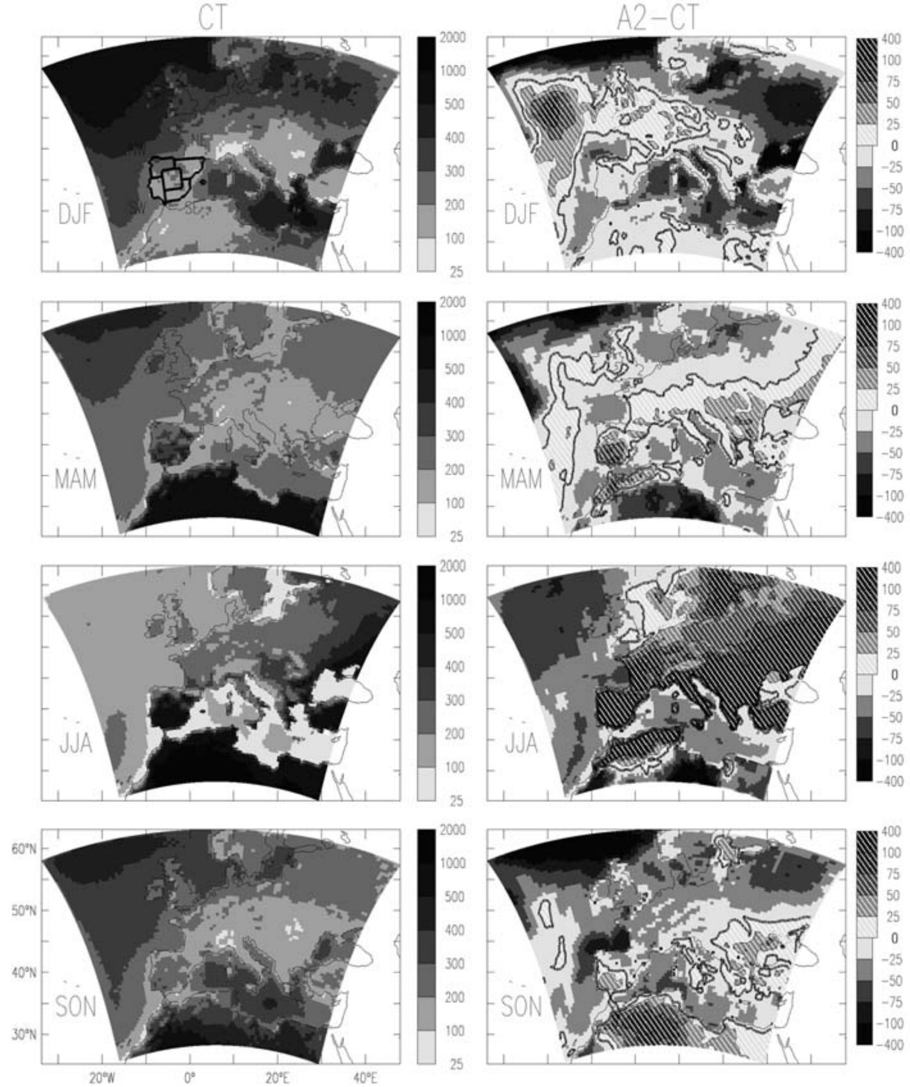

Figure 1.- Seasonal (from top to bottom: winter (December-January-February, DJF), spring (March-April-May, MAM), summer (June-July-August, JJA) and autumn (September-October-November, SON)) maps of vertically integrated TKE (in *kg* s^{-2}, as it is multiplied by air density) averages for present climate period (left column), and their change (A2 minus CT, right column).

Figure 1 shows TKEZ present climate (CT) and climate change (A2 minus CT) results averaged for the 4 seasons over the whole domain. The main features of TKEZ for present climate indicate (left column of Figure 1) maximum values (up to 1000 $kg\ s^{-2}$) during winter over the North Atlantic Ocean, and during the summer and spring over North Africa and the Iberian Peninsula (IP). Each maximum is related to a different atmospheric mechanism: winter results for the northwest part of the domain are associated with the typical quasipermanent low pressure systems present in that region, resulting in vertical ascent, and (turbulent) energy generation in the low and middle troposphere; meanwhile, the summer maximum of TKEZ in the southwest and in the vicinity of the Mediterranean sea is related to the summer maximum solar heating over a land surface, generating a maximum of sensible heat energy input inside the PBL. The other two seasons exhibit a transitional structure between the extreme winter and summer results.

Seasonal changes in TKEZ as a result of climate change (right column of Figure 1) are very different depending on the season. Summer results indicate an important increase in the turbulent energy over the land areas under future climatic conditions. This is also the case, although with less intensity, during spring over the southern half of Europe, autumn in some areas of Mediterranean Europe and Africa, and winter over northern France, southern Great Britain and parts of Central Europe. These TKEZ increases are similar to the summer temperature increases shown by PROMES RCM (Sánchez et al. 2004) and other similar RCM simulations (Christensen and Christensen 2007). The increased surface heating creates an additional energy supply that enhances turbulent activity. The correspondence between TKEZ and temperature increases is not totally consistent, as temperature increases are obtained where TKEZ decreases are present at times for some regions and periods. This is the evident, especially during spring and autumn, over the northern part of Europe. These changes can be associated with the increases in sea level pressure (as shown by Van Ulden et al. 2007). The increases in sea level pressure (not shown) are related to a decrease in baroclinic activity and corresponding reduction of frontal activity and turbulent energy generation. Another clear feature of TKEZ changes is their latitudinal structure during most of the year (except winter) over Europe, showing a north-to-south increase. Also a coastal gradient is present for some regions and periods, such as along the coastline of the Iberian Peninsula during summer. This TKEZ structure coincides with temperature increases (Sánchez et al. 2004) and an intensification of thermal lows (Hoinka and Castro 2003), giving rise to an enhancement of sea breezes.

The analysis of simulated PBL climatic conditions and their changes due to climatic change are focused hereafter over the Iberian Peninsula (IP). Several studies (Sánchez et al. 2004, Giorgi et al. 2004, Sánchez et al. 2007b, Christensen and Christensen 2007, Deque et al. 2007) with one or an ensemble of RCM projections have shown this region being one of the most sensitive to future climate change conditions for the end of XXI century. In particular, temperature could be increased up to 7 degrees during summer season, more than any other region over Europe, and precipitation will be reduced during most of the year. Sánchez et al. (2007a) indicate that this region would suffer an important hydrological stress during summer, due to increased sensible heat fluxes together with smaller increases or even decreases in latent heat fluxes from the surface. Therefore, we will present a more detailed analysis of climate change description related to boundary layer processes and magnitudes concentrated on this european region.

3.1. BOUNDARY LAYER CHARACTERISTICS OVER THE IBERIAN PENINSULA

Figure 1 showed in this region a clear coast-continent gradient of TKEZ changes due to climatic change conditions. For a more detailed analysis, IP region will be divided into 5 regions (shown in the top.left Figure 1) , one in the center of the Peninsula, and other four for the different coastal areas. The annual cycle characteristics of TKEZ and boundary layer height *(z_i)* are shown in Figures 2 and 3, respectively.

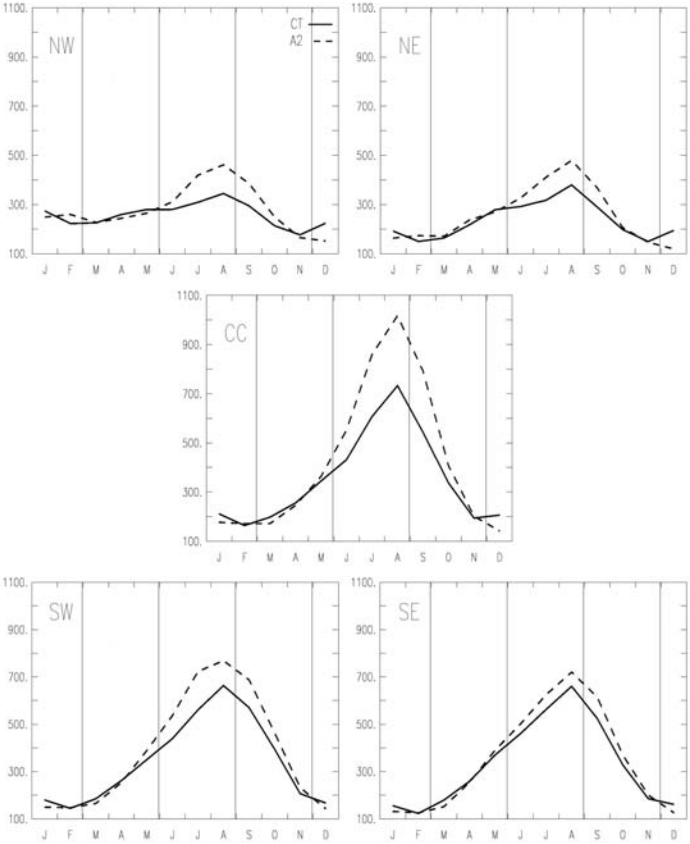

Figure 2.- Monthly timeseries climatology (30-year averages, from January to December) of integrated TKE values (*kg* s^{-2}) averages over the 5 regions shown in figure 1 over the Iberian Peninsula. Solid lines correspond to current climate (CT), and dashed lines to future climate change scenario (A2).

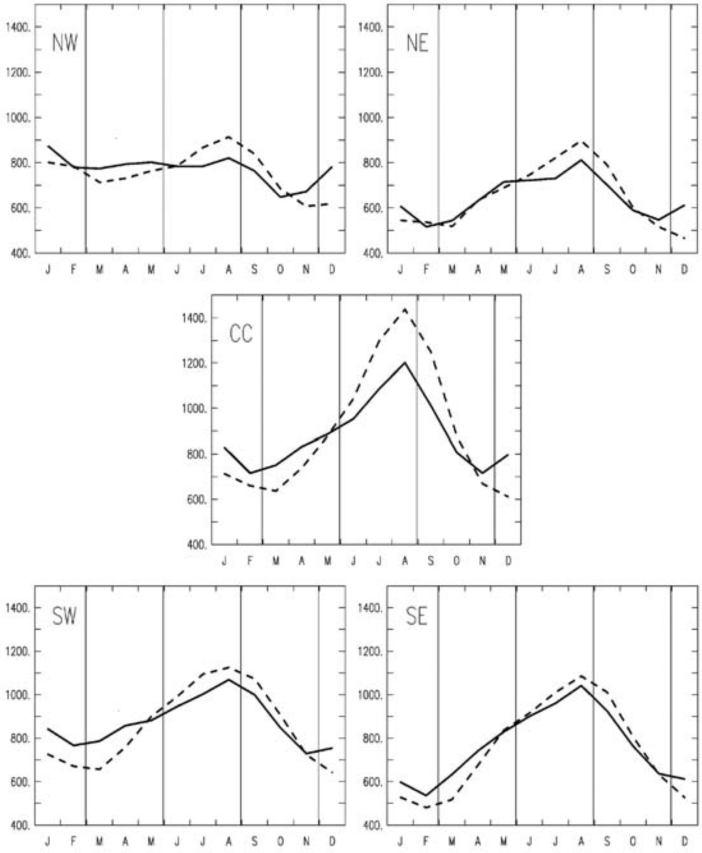

Figure 3.- As figure 2, but for boundary layer height (in m).

Boundary layer height is obtained from a very simple procedure, as a measure of the lowest atmospheric layers with a significant TKE value. It is obtained as the height where TKE becomes smaller for the first time than a minimum value threshold (0.05 $m^2\ s^{-2}$), similar to other PBL studies (Batchvarova et al. 1999, Shafran et al. 2000). PBL height is a very important parameter, both in dispersion and meteorological models, as it represents the volume of the atmosphere where the pollutants emitted at the surface and other components as water vapour, CO_2 or aerosols are mixed. All the regions exhibit a comparable qualitative behaviour, with a maximum increase of TKEZ for future climate during summer season and part of autumn (being maximum in August, up to 1100 $kg\ s^{-2}$), with just little variations during winter and spring. Central IP region (CC) presents the maximum values for present climate, but also the maximum increase for future climatic conditions among the chosen regions. Northern regions (NE, NW), show a very smooth annual cycle for present conditions, due to the smaller surface heating produced at the north of IP where vegetation is more abundant than in the southern part of the Peninsula. The summer maximum is much more clearly obtained for future climate period. SE and SW regions already have a clear peak during summer, which are just slightly increased. In relation with boundary layer height (Figure 3), a similar behaviour to TKEZ timeseries is obtained. CC is again the region with higher changes during summer, with a clear increase in height, meanwhile the other regions exhibit much smaller increases for that season. In fact, winter and partly in spring, z_i as computed here is even slightly reduced. As summer season shows the highest modifications due to climatic change conditions, a more detailed description of surface energy budget is shown in Figure 4.

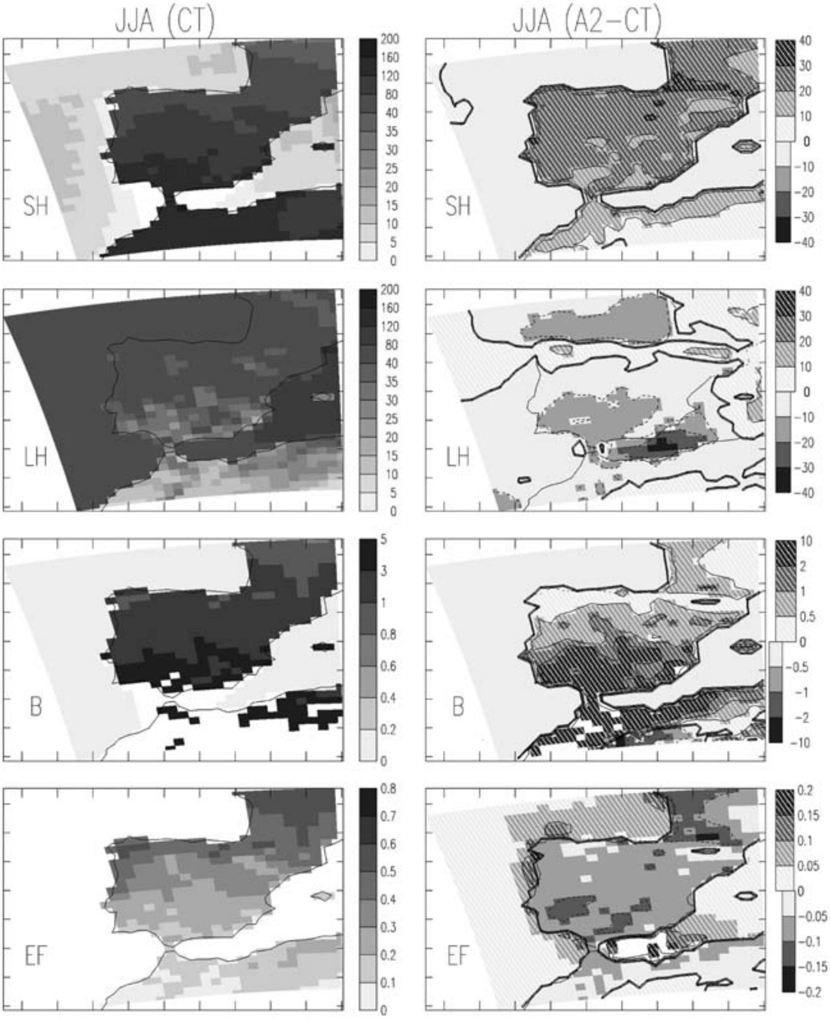

Figure 4.- Summer (JJA) 30-year averages, from top to bottom, of surface sensible heat flux (SH), latent heat flux (LH) (both in $W\ m^{-2}$), Bowen ratio (B), and evaporative fraction (EH) over the Iberian Peninsula. Present climate values are shown on left column, and changes from CT to A2 simulations on the right column.

Sensible heat fluxes (SH) are increased for future conditions, and latent heat fluxes (LH) are reduced, except on the northern part of the IP, where the humidity content of the soil is maintained for future climate conditions. This results in an enhanced Bowen ratio (B=SH/LH), and a reduced evaporative fraction (EF=LH/(SH+LH)=1/(1+B)). This increased Bowen ratio can be associated with an enhancement of convective activity, and thus TKEZ, resulting in a warmer atmosphere more than a cool and moist one (Oke 1988), and also can explain the higher boundary layer level obtained. The reduced EF values point towards an extension of semiarid areas over the Iberian Peninsula for future climatic conditions.

4. CONCLUSIONS

The analysis of boundary layer characteristics for present and future climatic periods under increased greenhouse gases conditions as seen with a regional climate model at 50 km resolution have been presented here. A clear increase in PBL energetics during summer over most of European domain, and specially over the Iberian Peninsula, being much smaller during the rest of the seasons for future climatic change conditions. These changes can be related to large scale features, such as baroclinic activity, or sea breezes changes. When studying the IP in detail the inner part of the IP exhibit the greatest changes in TKE and boundary layer height, compared with the coastal regions, enhancing the already pronounced annual cycle obtained for present climate. Surface energy budget over the IP during summer indicates that this region will reduce their latent heat fluxes an increase their sensible heat fluxes, pointing to an enhancement of their hydrological stress. A more deep analysis of boundary layer features is expected to be done, as this analysis is intended to be just a first step on this kind of climatic analysis from a PBL perspective.

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