Variaciones diarias del viento en superficie en terreno complejo

Diurnal surface wind variations over complex terrain

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Received: 19 June 2009
Accepted: 24 September 2009

RESUMEN
En este trabajo se presenta un análisis del ciclo diario del viento en los meses estivales (Junio, Julio y Agosto) utilizando observaciones y simulaciones numéricas en una zona de terreno complejo situada al noreste de la Península Ibérica. Mediante un análisis de componentes principales se han identificado dos modos de variación que explican el 96.8 % de la varianza. El primero contribuye con un máximo de viento por la tarde y un mínimo a últimas horas de la noche. El segundo modo de variación introduce un comportamiento local que favorece la aparición de un máximo o mínimo de viento en horas centrales del día. Se han examinado las contribuciones específicas de distintos procesos físicos. El primer modo está relacionado con brisas marinas. El segundo modo parece estar asociado con circulaciones inducidas por los gradientes horizontales de temperatura generados por la orografía, así como la homogenización ejercida por la mezcla turbulenta dentro de la capa límite planetaria.
Palabras clave: Variaciones diarias del viento; terreno complejo; PCA; simulaciones mesoscalares; WRF.

ABSTRACT
The diurnal surface wind variability during the summer season (June, July and August) over a complex terrain region located in the Northeast of the Iberian Peninsula is investigated using observations and a numerical simulation. Two main modes of variation were identified (96.8 % of the variance) by means of principal component analysis. The first one contributes with a wind speed maximum in the afternoon and a wind speed minimum at the end of the night. The second mode of variation introduces a local behaviour that contributes with a wind speed maximum or

minimum at central hours of the day. The specific contributions and relative importance of different physical mechanisms are investigated and discussed. The first mode is related to land- and sea-breezes. The second mode seems to be associated with thermal circulations induced by horizontal temperature gradients generated by the orography, and the homogenization exerted by turbulent mixing within the planetary boundary layer.
Key words: Diurnal wind variations; complex terrain; PCA, mesoscale simulation; WRF.

1. INTRODUCTION

The part of the atmosphere that is directly influenced by the presence of the earth's surface is known as the planetary boundary layer (PBL; Stull, 1988). Understanding of the atmospheric properties that characterize the behaviour of this layer and its variability is especially relevant for life since it is where most of the human activity takes place. Frictional drag, convection associated with turbulent heat transfer and terrain induced circulations are some of the physical processes contributing to the complicated wind variations that occur in this layer. Numerous theoretical and empirical studies focus on situations where some of the physical processes can be neglected in order to simplify the problem and thus facilitate its comprehension.

Assuming flat and homogeneous terrain, and constant geostrophic wind, the diurnal wind variability is reduced along the vertical direction. If constant eddy viscosity is also assumed, the steady state solution is the famous Ekman spiral (Ekman, 1905; Taylor, 1915). A more realistic model can be reached by taking into account the diurnal variation of the eddy viscosity along the day due to the solar cycle (Buajitti and Blackadar, 1957; Blackadar, 1957; Estoque, 1963; Krishna, 1968; Sheih, 1972). Introducing this new assumption, the steady state solutions are circles which radius increases with height (Sheih, 1972). These circular trajectories have been observed at upper atmospheric levels by several authors (Hearing and Borden Jr., 1962; Wallace and Hartranft, 1969; Crawford and Hudson, 1973). In particular, Crawford and Hudson (1973) went further on analyzing wind observations at six levels above the ground. They found that the wind is highly stratified during the night with higher wind speeds at higher levels; during the day, the ground is heated and the near surface air raises its temperature generating a turbulent transport that contributes to homogenize the properties within the PBL and therefore, producing a wind speed increase at lower levels and a decrease at higher levels. When the solar heating loses importance, the vertical transport is reduced and the wind recovers its initial stratification completing the cycle. Further refinements of the theory were reached including the effects of advective accelerations (Tan and Farahani, 1998) and an eddy viscosity varying with height (Zhang and Tan, 2002). Recently, numerical investigations based on large eddy simulations have been shown in agreement with these studies (Kumar et al., 2006).

Topographic features introduce additional diurnal wind variations due to changes in the horizontal pressure gradient force (Holton, 1967; Bonner and

Paegle, 1970). The heating and cooling of the ground over non-flat terrain generate horizontal temperature differences which, in turn, cause horizontal pressure gradients that produce diurnal wind circulations (Wagner, 1938; Defant, 1949; Whiteman, 2000). Even slight terrain slopes produce variations of comparable or even higher amplitude than those associated with eddy viscosity (Paegle and Rasch, 1973). Obviously, the diurnal wind cycles are more pronounced over complex topography regions due to the stronger horizontal temperature differences generated. Typical diurnal winds are up-slope and up-valley winds during the day over the valley walls and valley axis, respectively (Whiteman, 2000).

The heterogeneous surface properties are another source of diurnal wind variations (Hughes et al., 2007). Due to this heterogeneity, the surface responds in a different manner to the solar cycle, yielding a differential heating (and cooling) of the ground, which produces horizontal pressure gradient based circulations (Dai and Wang, 1999). A clear example is the contrast between land and sea that produces land-sea breezes (Miller et al., 2003).

The actual diurnal wind variation at a certain location is a combination of the previous physical processes which generate a wide range of diurnal circulations (Frenzel, 1962; Bonner and Paegle, 1970; Hisdal, 1972; McGowan and Sturman, 1996; Stewart et al., 2002; Nitis et al., 2005; Hughes et al., 2007).

This paper presents a preliminary investigation of the diurnal surface wind variations over a complex terrain area by using observations and a high resolution numerical simulation performed with the Weather Research and Forecasting modelling system (WRF; Skamarock et al., 2005). The study analyzes the influence of the different forcing mechanisms emphasizing the effects that the homogenization exerted within the PBL produces over the surface circulations in complex terrain.

2. DATA

The Comunidad Foral de Navarra (CFN), a region located in the Northeast of the Iberian Peninsula was selected for the study (Fig. 1). The orography of the region shows a variety of rich features broadly limited by two large mountain systems: the Iberian System to the South of the CFN and the Pyrenees to the North. Between them, the Ebro Valley crosses the region from Northwest to Southeast. The area is characterized by its strong wind conditions that have favoured the wind energy development during recent years (Fairless, 2007; García-Bustamante et al., 2008, 2009).

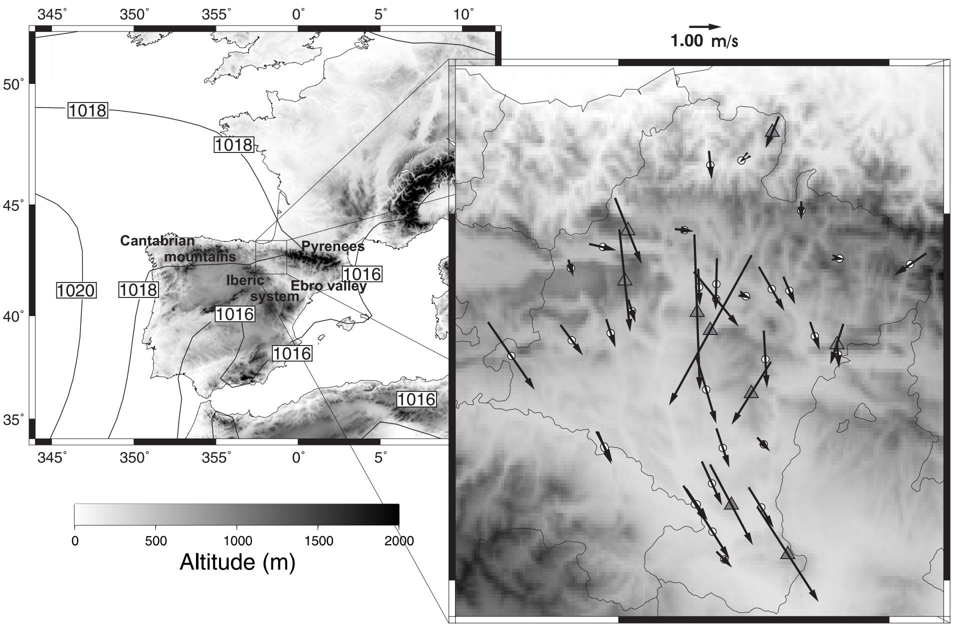

Figure 1. Location of the CFN within the Iberian Peninsula. Contour lines represent the mean sea level pressure (hPa) for the summer months from 1992 to 2005. The zoomed area displays the mean observational wind (arrows) for the same temporal period. The stations with mean wind speed higher than 5 m/s are represented with a triangle.

Wind observations from 41 meteorological stations are used in this study (see zoomed region in Fig. 1). The observational data comprise the period from 1 January 1992 to 7 October 2005 (Jiménez et al., 2009b). The wind observations were taken at 10 m above ground level, except for seven stations wherein the wind sensor is located at 2 m. The wind speed at these locations was extrapolated to 10 m using the power law with an exponent of 1/7 as it was done for instance by Pryor et al. (2005). The summer observations (June, July and August) were selected for this study. This choice is based on the stronger surface wind diurnal variations over land areas outside the tropics like the CFN during this season (Dai and Desser, 1999).

A summer season was simulated with the WRF model (Skamarock et al., 2005) in order to extend the spatial coverage of the observational network and thus, facilitate the physical interpretation of results. The model was configured at high horizontal resolution over the CFN, 2 km, in order to provide an accurate representation of its complex orography. A detailed description of the simulation can be found in Jiménez et al., 2009a.

3. DIURNAL WIND VARIATIONS

The mean sea level pressure from the ERA-40 reanalysis project (Uppala et al., 2005) for the summer months (June, July and August) from 1992 to 2005 is displayed in Figure 1. The whole Iberian Peninsula is under the influence of the Azores High which extends towards western Europe. This synoptic situation introduces northern geostrophic winds into the CFN that are channelled down the Ebro valley. The flow is intensified due to the pressure gradient over the Ebro valley (Jiménez et al., 2008, 2009b). This expected behaviour is in concordance with the observed wind for the same temporal period (see zoomed area in Fig. 1).

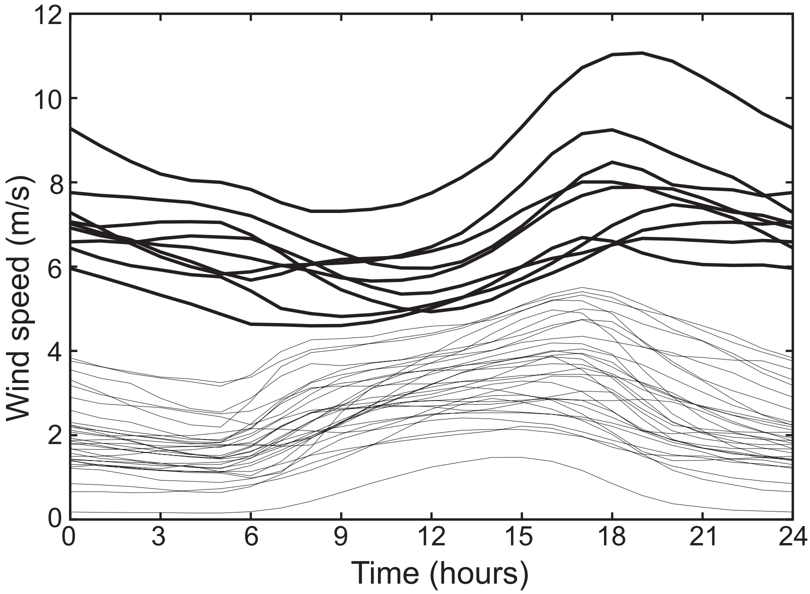

Figure 2. Mean diurnal wind speed variations at the different locations. The thick lines highlight stations with a mean wind speed higher than 5.0 m/s (triangles in Fig. 1).

The averaged wind speed diurnal cycles measured at the 41 stations are displayed in Figure 2. Large mean velocity variations become evident between the different locations, and range from less than 1.0 m/s to more than 10 m/s. There is a tendency to present a wind speed maximum in the late afternoon and a wind speed minimum during the night. The surface wind speed values are concentrated in a narrower interval during daytime, since locations with high wind speed tend to present a minimum and locations with low wind speeds a maximum. The stations with a mean wind speed higher than 5.0 m/s are highlighted with a thick line in Figure 2 and denoted with a triangle in Figure 1. They tend to be locations well exposed to the winds, like the mountain tops or hills in the Ebro valley (Fig. 1).

The characteristics of the wind diurnal cycles can be decomposed in two modes of variation (96.8 % of the variance) by means of principal component analysis (von Storch and Zwiers, 1999). Their loading maps and principal component time series are shown in Figure 3.

The first mode explains 71.8 % of the variance and its corresponding spatial pattern shows positive values over most of the region (Fig. 3a). It contributes to the diurnal cycle with a minimum at the end of the night and a maximum in the afternoon (Fig. 3c). The reasons for this behaviour become evident after analyzing the wind anomalies throughout the day (Fig. 4). The anomalies show a noticeable veering, being in the opposite sense to the mean flow at the end of the night (Fig. 4b) and in the same sense during the afternoon (Fig. 4d).

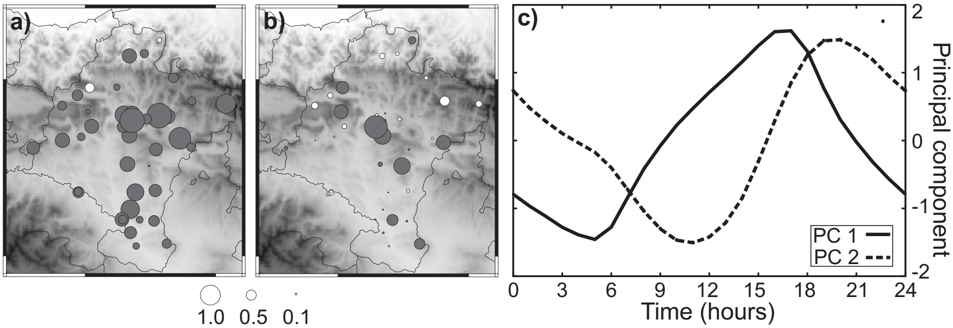

Figure 3. Loading map of the first (a) and the second (b) principal modes. The radius of the circles is proportional to the magnitude of the load and the color indicates the sign, white for positive values and black for negative. The principal components are also displayed (c).

For an understanding of the physical process that causes the observed behaviour (Fig. 4) the WRF simulation is analyzed. The simulated wind anomalies are displayed in Figure 5. The diurnal evolution shows resemblances with the observed wind anomalies (Fig. 4). In particular, it reproduces the veering throughout the day with an opposite sense to the mean flow at the end of the night (Fig. 5b) and the same sense in the afternoon (Fig. 5d). This behaviour is attributed to the land- and sea-breezes generated by the different response of land and sea to the solar cycle (Dai and Desser, 1999). During the day, the land increases its temperature faster than the sea and causes a pressure fall down which creates a horizontal pressure gradient between land and sea areas that establishes flows towards the interior of the CFN; during the night, the radiative cooling decreases the land temperature faster than the sea and the horizontal pressure gradient changes its sense reversing the flow. The meridional cells associated with the land- and sea-breezes become evident in the simulated wind in a North-to-South vertical cross section over the area.

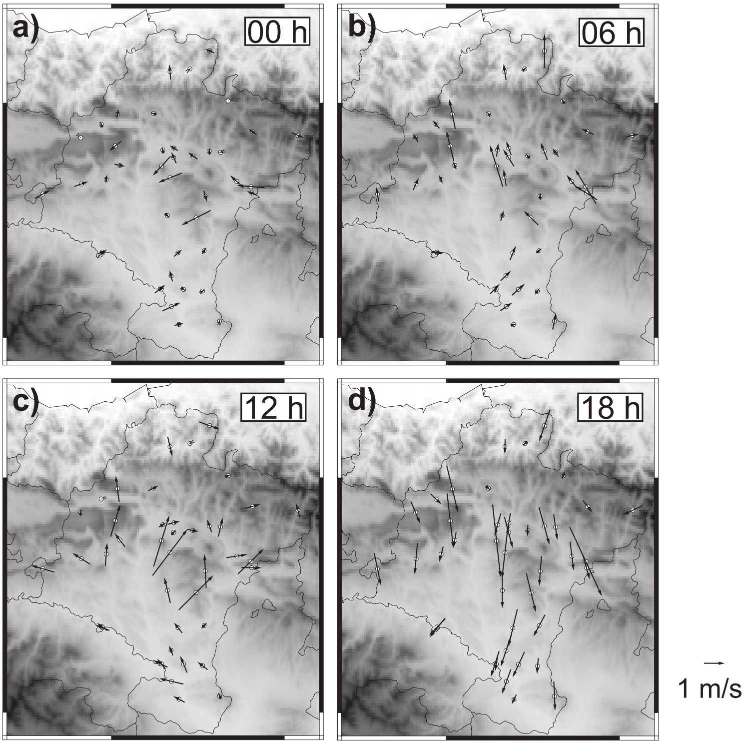

Figure 4. Observed mean wind vector anomalies at a) 00, b) 06, c) 12 and d) 18 UTC.

The second mode of variation explains 25.0 % of the variance and it is characterized by the presence of a minimum at 11 UTC (Fig. 3c). Accordingly, it tends to show positive loads at locations that present a mean wind speed higher than 5.0 m/s (Fig. 1) and near zero or negative ones in the rest (Fig 3b).

An understanding of the physical process that produces this behaviour can be achieved analyzing the wind anomalies of the simulation (Fig. 5). The circulations induced by the differential heating of land and sea associated with the first mode of variation are fully developed towards the sea at 6 UTC (Fig. 5b) and towards inland at 18 UTC (Fig. 5d). On the contrary, the anomaly fields at 0 UTC (Fig. 5a) and 12 UTC (Fig. 5c) show that the influence of the circulations is limited to the northern areas. The circulations of the interior seem to be controlled by the horizontal temperature gradients induced by the orography. In particular, the anomalies at 12 UTC (Fig. 5c) show up-valley and up-slope winds in the Ebro basin in concordance with observations (Fig. 4c). These circulations present the opposite sense to the mean wind (Fig. 1), and thus contribute to reduce the wind speed during the day.

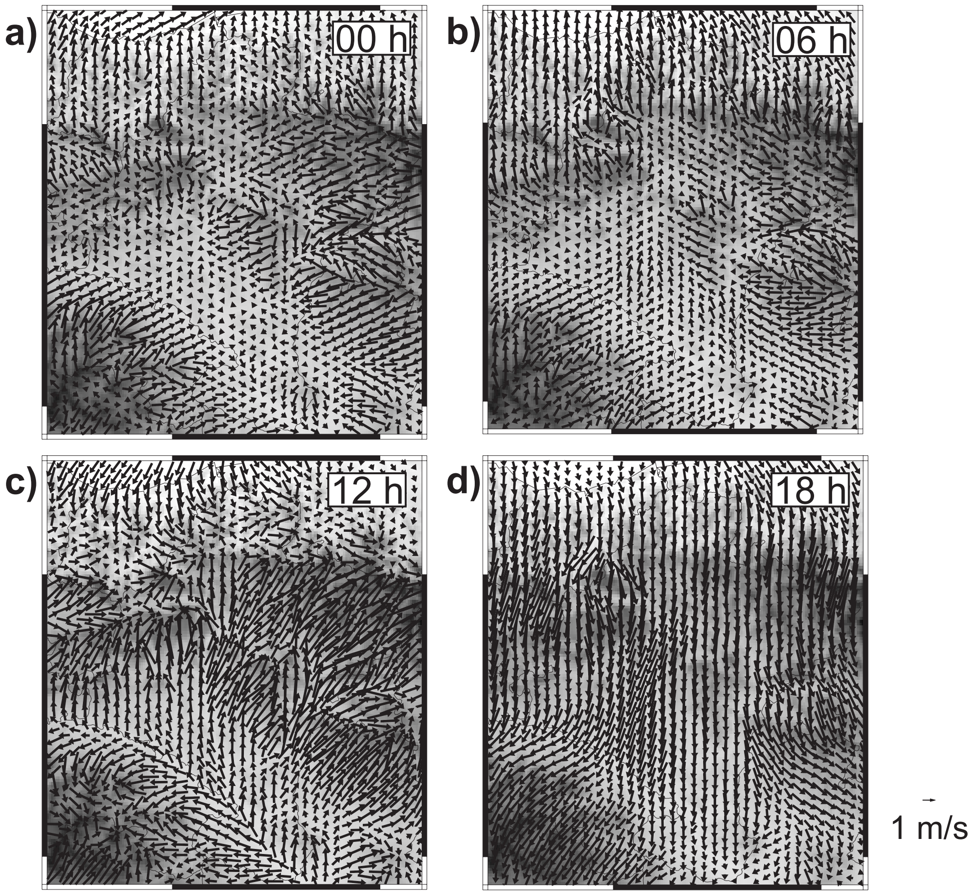

Figure 5. Same as Figure 4 but calculated with the wind from the WRF simulation.

Analyzing the dispersion diagram of the loads of this second mode versus the mean wind speed at each site (Fig. 6) provides further comprehension of the physical processes contributing to this mode of variation. Both variables are correlated (r = 0.94). In particular, locations with high mean wind speed show a positive load whereas locations with the weakest wind speeds show a negative one. Since the associated principal component shows a minimum at 11 UTC (Fig. 3c), the contribution of this mode is responsible for the tendency to show similar wind speed at the different sites during daytime (Fig. 2). This behaviour can be interpreted as the action of a physical mechanism which tries to homogenize the wind speed during the day. This suggests that a possible explanation for the convergence of the wind speed time series could be associated with the effects of turbulent mixing which tries to homogenize the physical properties within the PBL.

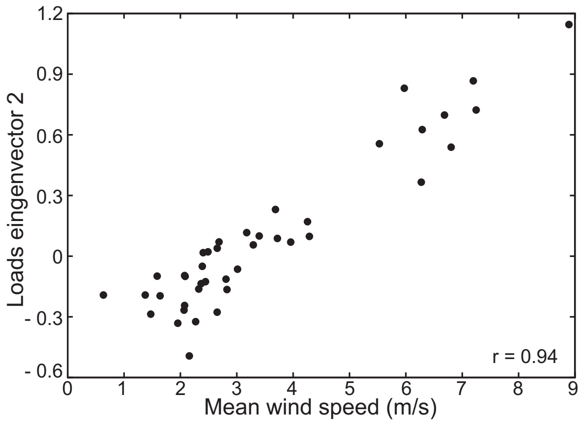

Figure 6. Loads from the second principal mode (Fig. 3b) *versus* the mean wind speed.

The previous hypothesis is reinforced after a rotation of the two principal modes in such a way that the second mode presents maximum contribution at 12 UTC. The rotated principal modes are shown in Figure 7. The first rotated principal component appears in its positive phase (Fig. 7a) presenting a maximum at 18 UTC and a minimum at 6 UTC (Fig. 7c) that can be related to the land- and sea-breeze circulations. It shows a reduction of its magnitude with respect to the un-rotated principal component during the day (Fig. 3c). This reduction occurs in benefit of the second principal component which now presents a clear resemblance with the solar heating (Fig. 7c), a maximum at 12 UTC and constant values during the night. This mode shows positive or negative loads depending on the specific location of the station (Fig. 7b). The negative contributions occur at stations with the highest winds causing a minimum during daytime and therefore with a structure very similar to the classification of stations shown in Figure 1.

The previous considerations can be evaluated using the WRF simulation. However, the model does not reproduce the wind evolution at the windiest locations (Fig. 8a). The simulation shows a tendency to present a minimum at the end of the night and a maximum during the afternoon in concordance with the land-sea breeze effects. The time series present similar wind speeds during the day, but no station shows higher wind speeds during the night. A possible explanation for this could relay to the extreme location of the stations that show the highest wind speed. These stations tend to be located at mountain tops or hills in the Ebro valley (Fig. 1) that are not well resolved at the spatial resolution used in the simulation (2 km). If it can be argued that the mountain tops are well exposed to the quasi-geostrophic winds with a weak surface friction, the observed wind at these sites can be represented by the simulated wind at the true elevation of the stations. The wind speed evolutions at the true altitude of the stations are displayed in Figure 8b. The higher wind speeds during the night are now reproduced at most of the sites, and the simulated wind shows a better concordance with observations (Fig. 2).

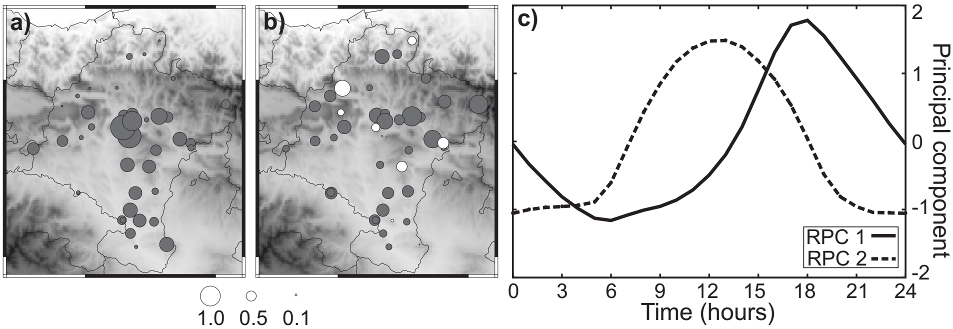

Figure 7. Same as Figure 3 but for the rotated principal modes.

A more detailed examination of the surface wind simulation reveals weak secondary minima at central hours of the day superimposed to the mentioned maximum associated with the homogenization within the PBL (Fig. 8a). In the case of the mountain stations it could be a consequence of the up-slope circulations produced by the horizontal temperature gradients induced by the topography (Fig. 5c). The minima are of considerable less magnitude than those found at the true height of the station (Fig. 8b) which are also in better agreement with observations (Fig. 2). This fact would point to the homogenization exerted within the PBL as the main contributor to the second mode of variation.

4. CONCLUSIONS

The diurnal surface wind variations over the CFN were analyzed. Two main modes of variation were identified. The first one contributes to a wind

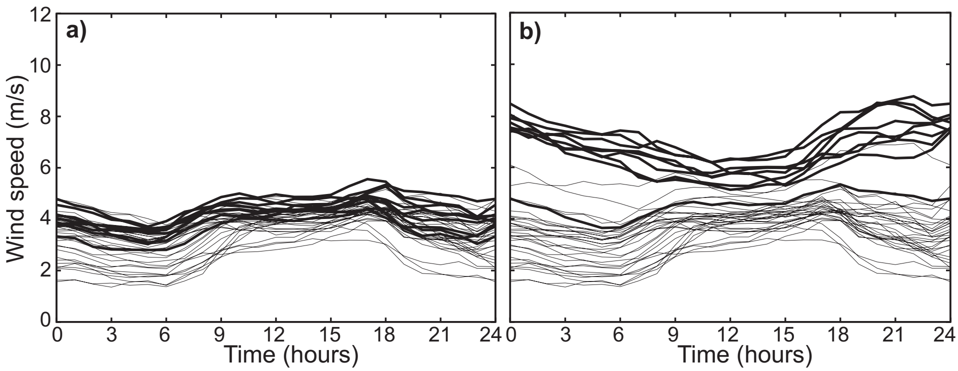

Figure 8. Same as Figure 3 but for the simulated wind speed at 10 m above ground level (a) and interpolated to the actual height of the station (b). The thick lines represent the stations that show a mean wind speed higher than 5 m/s (Triangles in Fig. 1).

speed minima during the night and a wind speed maxima in the late afternoon. It is associated with land- and sea-breeze circulations induced by the differential response of land and sea to the solar cycle. The second mode of variation introduces a local behaviour that tends to homogenize the surface wind speeds during the day. Terrain induced circulations like up-valley or up-slope winds seem to contribute to this mode. However, they seem to play a secondary role in comparison with the homogenization exerted by the turbulent mixing within the PBL.

The WRF simulation reproduces the wind speed evolution associated with the sea-land breezes and the similar wind speeds during the day. However, the simulation does not reproduce the high wind speeds observed during the night at certain locations. This misrepresentation was attributed to an insufficient horizontal resolution to resolve the extreme locations of the mountain tops or hills wherein the highest winds are observed.

5. ACKNOWLEDGEMENTS

We would like to thank the Navarra Government and the ECMWF for the free access to their datasets. This work was partially founded by the Projects IN-VENTO CGL2005-06966-C07/CLI, PSE –Minieólica PSS-120000-2007-71 and AVAVIP CGL2008-05093/CLI.

Queremos dedicar este trabajo a la memoria de la Prof. Elvira Zurita. Su actitud en el desarrollo de la vida académica y su ética profesional constituyen un referente que no olvidamos. Varios de los firmantes de este trabajo fueron alumnos y compañeros suyos durante años. Hubiésemos querido disfrutar de su humanidad y sus enseñanzas por más tiempo y no tener que lamentar la tragedia de su pronta desaparición. Nos queda el recuerdo de los momentos vividos en la facultad y lo que con ella aprendimos; también la determinación de transmitirlo a futuros alumnos y compañeros.

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