Final report MedCLIVAR ESF-Exchange Grant

Title: ANALYSIS OF WIND FIELD VARIABILITY IN NORTHEASTERN IBERIAN PENINSULA: relationship with the large scale atmospheric circulation, estimation of uncertainties, reconstructions and future projections.

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Applicant's name: Elena García Bustamante, Universidad Complutense de Madrid (UCM) and CIEMAT, PalMA Research Group, Dpt. Astrofísica y Ciencias de la Atmósfera. Ciudad Universitaria s/n, 28040, Madrid; Spain *elena.garcia@fis.ucm.es*

Host Institute: Dr. Elena Xoplaki, Bern University. Institute of Geography. Climatology and Meteorology group, Hallerstrasse 12, 3012 Bern, Switzerland.

1. Project description and objectives

Exploring the climate variability and the projection of possible future climate changes at the regional scale entails the search of strategies which properly describe the complex interaction between synoptic atmospheric circulation and local features, like topography, vegetation, land-sea interactions, etc. However, the evaluation of the downscaling methodologies, that attempt to cover the gap between the information provided by GCM_s and the reliable estimations required at the regional scale, can be still considered a challenge since the applications of such techniques in many regions remain yet unexplored (Wilby et al. 1998; Hanssen-Bauer et al. 2003; Wood et al. 2004; Haylock et al. 2006; Schmidli et al. 2006; Meehl et al. 2007).

The surface wind field is subjected to a high spatial and also temporal variability since it can be considered as a local response to the synoptic forcing, and this inherent feature of the wind not only yields an additional difficulty to its diagnosis and prediction but also provides the subject with a valuable scientific interest. The analysis of the wind speed variability at the different timescales involves practical applications which range from the short term wind forecasts to the climatological wind variability changes assessment (Marzban and Stump 1998; Darby 2005; Yan et al. 2006; Zhang et al. 2006). In addition, recently a special attention has been paid to the wind energy development in many regions of the world as an alternative and clean energy resource (Celik 2003; Faulin et al. 2006).

The basis of the project relies on the identification of possible associations between the large scale atmospheric circulation and the local wind field and also the wind power generated in a region within the Iberian Peninsula at monthly timescale. Thus, the present work is focused on the application of a statistical downscaling technique which has proven adequate skill in predicting other variables like precipitation or temperature (González-Rouco et al. 2000; Xoplaki et al. 2003a,b) using information from the large scale circulation. Additionally, the predictability of the regional wind field can be further assessed by analyzing the associated uncertainties that arise from the large scale influence and also those related to the various methodological aspects. The combination of both sources of uncertainty provides a more reliable estimation of the wind field variability over the area. Moreover, a special emphasis will be given to the assessment of the long term variations of wind and wind power over the region in order to infer the most important features of the variability at interannual and decadal timescales as well as the evaluation of potential anomalous periods or possible long term trends. This will be done by analyzing the wind and wind power climatology reconstructions for the last 350 years.

Although previous evaluations of wind related variables at the regional scale have been carried out for different areas in the world (Kaas et al. 1996; Bogardi and Matyasovszky 1996; Pryor and Schoof 2005; Pryor et al. 2005; Najac et al. 2009) the statistical approach of the present study is applied for the first time on wind related variables. One of the more interesting aspects of this work is the study area, a region of complex terrain in the northeastern Iberian Peninsula that constitutes an ideal frame to testing downscaling methodologies. In addition for this specific exercise, wind power production observations are available thus allowing for an estimation of the predictability of non-meteorological variables that can be put in the context of ecosystem oriented studies. There are some studies assessing the climatic evolution of the wind field in several regions applying a certain emphasis in the variations of the energy carried in the wind as representative of the wind power (Pryor and Schoof 2005; Pryor et al. 2005). However, there are no previous works assessing the power production spatial and temporal variability at different timescales and its relation with the synoptic circulation based on the use of real outputs of wind farm turbines as in this study. Finally, the evaluation of the associated methodological uncertainties constitutes an additional feature of the case study contributing to the uniqueness of the project since the assessment of the methodological uncertainty in the context of a statistical downscaling technique is not extensively explored yet in the scientific literature.

2. Results of the work

a. Analysis of the large scale influence and relations with the surface wind field over the Northeast of the Iberian Peninsula

Navarra, in the northeastern Spain (Fig. 1), is a region of intricate orography surrounded by two large mountain ranges, the Pyrenees and Cantabrian systems. It is worth noting the presence of the Ebro Valley, that channels and accelerates the surface flow. The wind speed observations were recorded at 29 meteorological stations for a 14 years period from 1992 to 2005 (Jiménez et al. 2008a,b). In addition, observational data from 3 wind farms (squares in Fig. 1) were also used in this study. These measurements consist of hourly wind speed and wind power production records spanning throughout 1999 and 2003 in the longest case. Further details on the wind farm data can be found in García-Bustamante et al. (2008, 2009).

The method applied is the canonical correlation analysis (CCA), a multivariate statistical technique that isolates the associations between the predictor and predictand variables that are optimally correlated (Hotelling 1935, 1936; Bretherton et al. 1992) on the EOFs space. The analysis is performed with the wind speed components (zonal and meridional) as predictand field. This allows for taking the directionality of the flow into account when searching for the relations between the surface and the large scale circulation. A reference case is presented (variations of this initial set up of the model will be shown later in the sensitivity

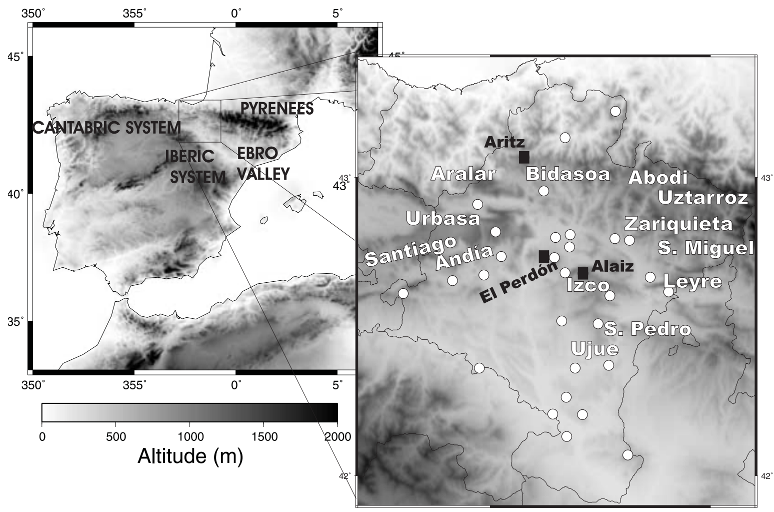

FIG. 1. Location of the 29 meteorological stations (white dots) and the 3 wind farms (black squares) providing the wind and wind power data.

analysis) where an equal number of EOF_s (4) for the predictand and the predictor variables were retained. Regarding the last, a combination of two large scale fields taken from the ERA-40 reanalysis and analysis from the ECMWF forecast model were employed to represent the global circulation: the 850 hPa geopotential height, ϕ_{850}, and the 500-850 hPa thermal thickness, $Z_{500-850}$. The analysis is limited to a geographical area including the western North Atlantic area, the Iberian Peninsula, the British Isles, the westernmost part of the European continent and part of the Mediterranean area. The coherent regional wind and synoptic patterns were analysed through the two first canonical modes which are then used to build up the regression model for the estimation of the predictand (Kaas et al. 1996). Here, for brevity, we present only the first pattern. The first CCA pair of maps (CCA1) account for a 27$\%$ (32$\%$) of the variance of the large scale predictor (predictand). They are represented in Figs. 2a and 2b respectively, together with their amplitude time series (Fig. 2c). The first large scale canonical pattern depicts a dipole structure with positive anomalies over the Atlantic region, at the western side of the Iberian Peninsula. Negative anomalies are located over the northeast of the British Isles, centred over the Scandinavian Peninsula. The simultaneous CCA1 pattern for the regional wind components, present a NW-SE anomalous wind which can be related to the so-called '*Cierzo*', a very well known wind in the area (de Pedraza 1985). Thus, the contribution to the pressure gradient between the two anomaly centers favours this predominant direction of the geostrophic wind field over the region. At the surface, the presence of the Ebro Valley along a NW-SE axis through the region induces a strong channeling effect (Figure 2b). The characteristic pattern obtained is then the combination of the synoptic structure modulated by the orographic configuration of the area under study. It is possible to appreciate a very good agreement between the series describing the temporal evolution of both, predictor and predictand canonical patterns (correlation 0.87).

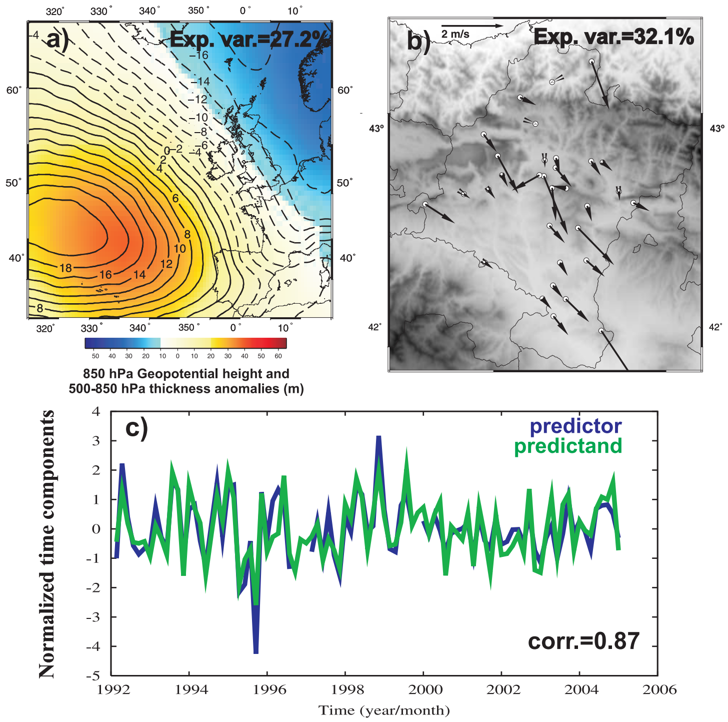

FIG. 2. Canonical spatial patterns and amplitude time series of the first CCA mode (CCA1): (**a**) predictor (large scale) CCA1 pattern, shaded is the ϕ_{850} hPa and curves represent the $Z_{500-850}$ hPa (positive solid and negative dashed); (**b**) predictand (local wind) CCA1 pattern and (**c**) normalised time series of the CCA1 for predictor (blue) and predictand (green).

After the calibration of the method, the cross-validation process allows for obtaining wind field estimation series for the whole observational period by extracting a single monthly observation and using the rest of available months to obtain the corresponding estimation, thus using the linear relation found between predictors and predictand during the calibration period. This process is repeated subsequently for the whole time series. To a good degree the estimations present temporal concordance with the observations. The correlations between the spatially averaged estimations and observations are 0.78 and 0.82 for the zonal and meridional wind components respectively. As expected, estimations are better for the meridional wind component since this wind component evidences a more deterministic behavior than the zonal one, this fact is mainly due to the constraints imposed to the flow by the the orography of the region and the presence of the Ebro Valley. Regarding the variance of estimations, values are to some extent underestimated with respect to observations. This loss of variance is inherent to the methodology applied since the CCA does not enhance the variance of the predictand field. Instead the CCA maximizes the correlation between the two sets of variables sacrificing the explained variance in each case (von Storch and Zwiers 1999).

b. **Evaluation of the uncertainties associated to the methodological variance and to the large scale predictor fields influence**

An evaluation of the uncertainties associated with the regional wind field estimations was conducted. First an assessment of the methodological sensitivity is considered. The approach consists in allowing a certain degree of variability in each one of the parameters that has to be defined in the model set up. The uncertainty associated with the large scale atmospheric circulation is also taken into account by employing various datasets to provide the predictor or large scale field information.

The parameters *a priori* defined in the model that can be varied to explore the methodological variance are a) the size of the large scale domain, where different windows covering from smaller areas over the region under study to larger windows over the North Atlantic area have been defined; b) the ERA-40 field selected as predictor: several dynamical and thermal variables and/or combinations of 2 or 3 of them were explored; c) the number of EOFs and CCAs retained for the analysis and d) the number of steps considered during the cross-validation process.

The large sample obtained when all parameters are allowed to vary jointly (aprox. 63.000) is divided in ten groups of equal frequency, so that the deciles are represented for the regional time series in Figs. 3a and 3b (zonal and meridional wind components, respectively) together with the observations (black), the reference estimate (gray) and the maximum and minimum values (dashed-dotted orange). It is worth to note that the uncertainty areas maintain the variability of the observations during the whole calibration period (1992-2005), pointing out the robustness of the methodology in estimating the wind field since it evidences that the performance of the model is not largely dependant of the configuration selected. As expected, the uncertainty area and its variability along the calibration period is larger in the case of the meridional component (Fig. 3b). It is interesting to observe that most of observations are confined within the uncertainty intervals thus, providing additional robustness to the procedure. In the case of the zonal (meridional) component a 15% (9%) of the observations fall out of the area.

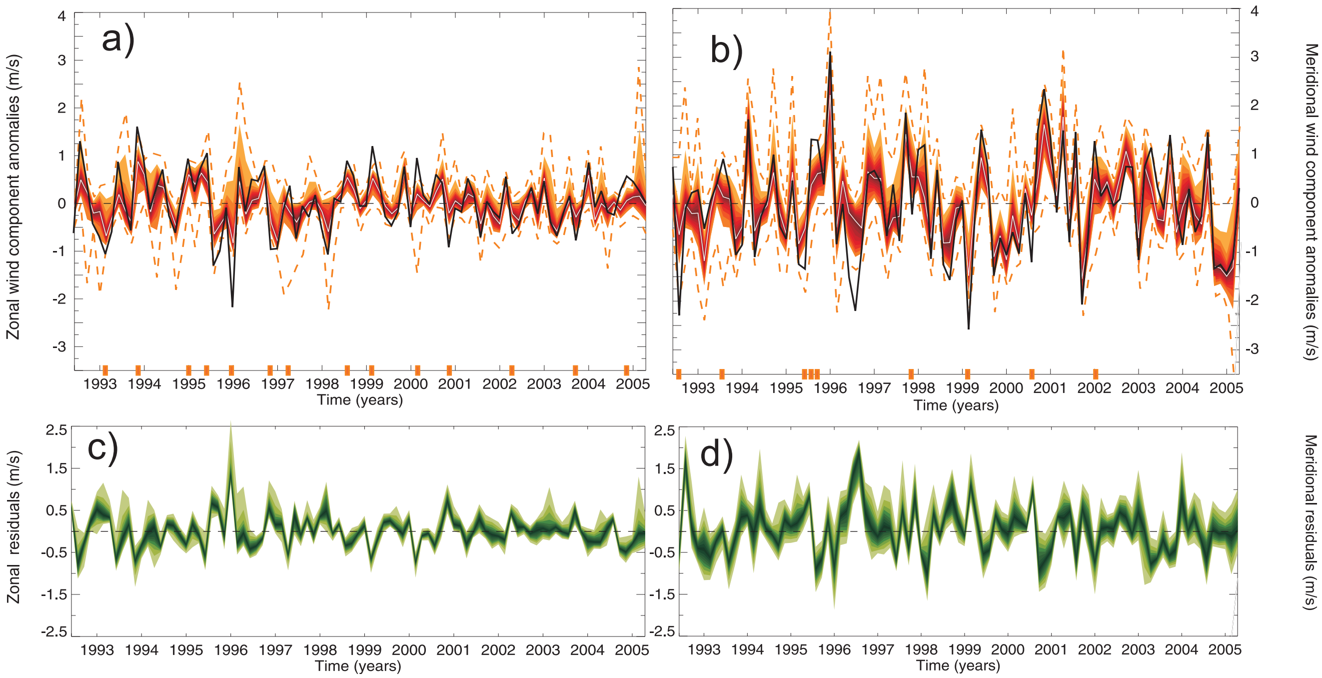

FIG. 3. Top: Deciles distribution (degraded orange area) with respect to the median of the regional (spatially averaged) time series, **a**) is the zonal and **b**) is the meridional wind component together with the observations (black), the reference case estimate (gray) and the maximum and minimum values (dashed-dotted orange). Bottom: Regional residual (estimations minus observations) time series for the zonal (**c**) and meridional (**d**) wind components.

The distributions of the deciles of the residuals (estimations minus observations) are represented in Figs. 3c and 3d for the zonal and meridional wind components, respectively, for a brief insight at the temporal variation of the errors. It can be observed for both (zonal and meridional) series that there are no significant trends so the variance of residuals is constant along the calibration period. The structure of the residual series, each one with its corresponding levels of variance, is noisy and still resembles the variability of the observations . Thus, as the residuals represent the portion of the observations variance that is not explained by the model this points out to a 'robustness' of the model in the sense that, if the model is not able to reproduce the variability of the observed value at certain time steps whatever is the combination of parameters selected, the model will under/overestimate this variance.

To have an insight at the possible impacts concerning variations in the datasets that act as large scale predictors, two comparable experiments were considered: in one case the SLP field from the ECMWF reanalysis and analysis is used as single predictor allowing the rest of parameters to vary, namely the large scale domain size, the number of retained EOFs/CCAs and validation steps. On the other hand, the SLP field from three additional datasets are employed: the observed NCAR SLP (Trenberth and Paolino 1980) from 1899 to 2005, the Hadley Centre historical SLP (Allan and Ansell 2006) and the reconstructed SLP for the North Atlantic area from 1659 to 2000 by Luterbacher et al. (2002). Similarly every parameter can be varied. These experiments were conducted only for the case of the SLP predictor to provide a common frame in which the two different cases (single and multimodel) could be compared. Once all the CCA experiments are accomplished, two deciles distributions are obtained (the ensembles of estimations are spatially averaged to provide the regional time series and the deciles distribution with respect to the central value are then calculated for each case). It is possible to analyse for instance the differences or residuals between these two distributions. The analysis revealed that although a certain influence in the uncertainty due to the use of the large scale predictors coming from different datasets has been found, the differences to the case when using only the ECMWF reanalysis and analysis fields were not large.

c. Reconstruction of the past centuries wind and wind power climatology

The assessment of the past climate at the regional scale can provide an additional understanding of the natural and forced levels of climate variability in the region under study for a wide range of timescales, ranging from intra- to inter-annual or decadal timescales. The set of experiments of the single and multi model exercise were used to obtain the long term past estimations of the wind field. Regression models were calculated using the canonical patterns obtained in the previous steps. With them, past projections of the wind were calculated employing as predictor fields the available information for a) the last five decades fields from ERA-40 reanalysis, 1957-2002 and the analysis of the operational ECMWF global model ($recon_{era40}$), b) the information regarding the past 20^{th} century is provided by the NCAR observed SLP ($recon_{ncar}$), c) the period from 1850-2004 the Hadley Centre historical SLP was also used to obtain the reconstruction $recon_{had2}$ and finally, d) Luterbacher et al. (2002) SLP reconstruction provides the wind speed estimates back to the 17^{th} century ($recon_{Luterb}$). The reconstructed series of the regional wind are represented in Figs. 4a and 4b for the zonal and meridional components, respectively. The associated uncertainties related to all the possible variations of parameters entering the model were also projected and represented.

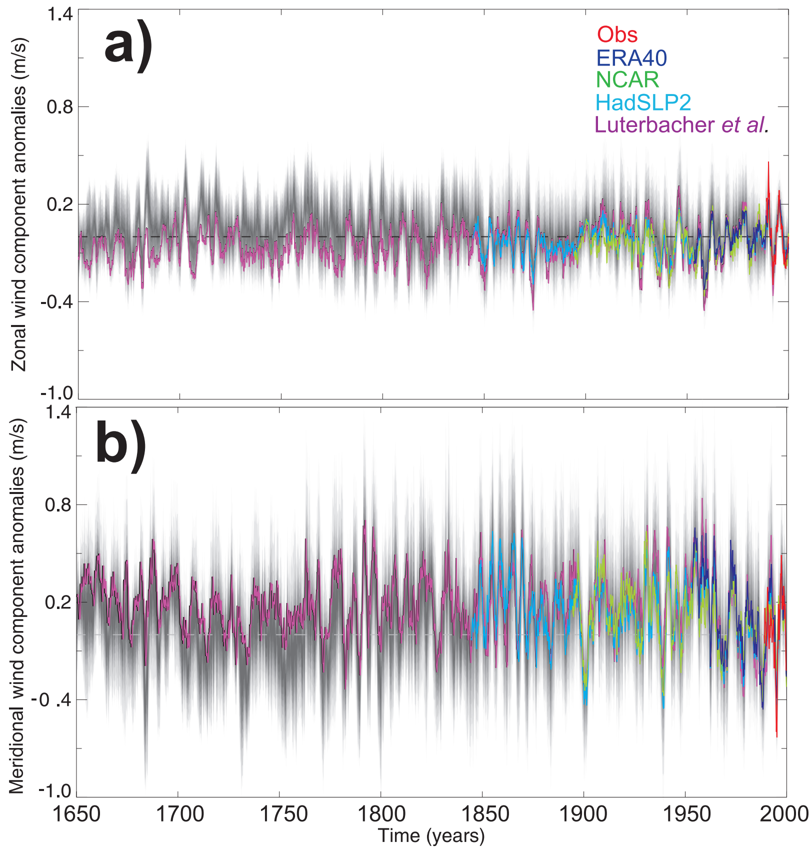

FIG. 4. Wind climatology reconstruction and its associated uncertainty for the zonal (**a**) and meridional (**b**) wind components respectively. In gray the deciles with respect to the the median distribution of the uncertainty are represented, red series are the observations, dark blue series stands for $recon_{era40}$, green is $recon_{ncar}$, light blue represents $recon_{had2}$ and violets is $recon_{Luterb}$ in the reference case as in the example showed with the wind estimations in the second section.

Series in Fig. 4 that correspond to the reference experiment as in the first section, show a reasonable agreement between them in their corresponding overlapping periods and also during the calibration period. The $recon_{Luterb}$ series shows the larger variance. This fact is due to the distinct period of calibration in this latter case, since the reconstruction finishes in 1999.There are some periods with anomalous higher wind velocities as for instance in the second half of the 17^{th} and 18^{th} centuries. Previous works address interestingly an increase of wind extremes during the colder period of the Little Ice Age and especially during the Maunder Minimum (1640-1715) apparently due to a southward shift of the storm tracks approximately between 20^o and 35^oN (Raible et al. 2007). However, no significant trends can be found in the whole reconstruction period. Despite the former, it is apparent the presence of a certain tendency of the zonal wind component towards positive values and the corresponding tendency to the negative ones in the case of the meridional component from the second half of the 20^{th} century till the present. This can be interpreted as a strengthening of the first mode of circulation found during the calibration analysis (Fig. 2a) which represents intensification of northwesterly winds. This reinforcement of the meridional circulations was also found by Davis et al. (1996). The reconstructed climatology as well as the projected uncertainty anomalies reveal the presence of intra- to inter-annual and decadal variability. It can be said that the variability of the uncertainty projections remain in reasonable levels of variance compared to those of the reference reconstructions. It is worth to mention that in the case of the longest reconstruction ($recon_{Luterb}$) the reference experiment showed in Fig. 4 falls close to the extremity of the uncertainty distribution. The reasons for this biased behaviour are still not clear and it is being explored at present.

d. **Application of the downscaling approach to the case of the wind power production**

A similar analysis as in the case of the wind components was applied to the wind power production. It is illustrative of a case of impact study where the aim is to assess the predictability of a variable that is not meteorological but directly dependent on the evolution of the wind field and its variability and then, requires reliable climatic information at the local or regional spatial scales. The main purpose was to explore the relation between the large scale circulation and the wind power production in the region under study at monthly timescales following a similar approach as employed in the previous sections to analyse the wind field variability. García-Bustamante et al. (2009) showed the existence of an empirical linear relation between the wind speed and the wind power at monthly timescales through an evaluation in which available wind power data from several wind farms at the same region in the northeastern Iberian Peninsula were employed. They evidenced a linear behaviour between both variables even though at shorter timescales the expected relation between wind speed and wind power is cubic. The aim here was to test whether the linear relation evidenced between the large scale circulation and the local wind in the region can be extended to the case of the monthly wind power production.

The first large scale canonical pattern (not shown) consists in a negative anomaly centre located westward the British Isles. It resembles to a good degree the second pattern found in the case of the wind speed analysis but with a certain displacement to Northwest. The corresponding local pattern shows a dipole with positive anomalies in the northern part of the region and negative wind power production anomalies in the centre. This is coherent with the wind speed pattern that it would have been obtained if the analysis was performed for the same period (1999-2003) and the same number of EOFs/CCAs with the wind speed as predictand, i.e., more windy conditions in the Northern and Northwestern areas and a decelerated flow in the centre of the region and along the Ebro Valley. The canonical correlation is 0.89. The validation was accomplished as in the case of the wind velocity and then, the wind power estimations for the period 1999-2003 were obtained. It evidenced the presence of some predictability for at least two of the wind farms and a poor performance of the 3^{rd} location. However, the main hypothesis is substantiated at two of the locations and this can be considered as indicative of a transfer of the linearity between the large scale and the non-meteorological variable at monthly timescales via the monthly wind velocity. Thus, the variability of the wind power production over the region can be considered as governed by the synoptic circulation and this will prove some utility as shown below.

The estimation of wind power through a direct downscaling can be undertaken with some simple variants. An alternative technique consists of the downscaling of the wind field and afterwards the translation of the wind estimation into wind power by using a transfer function as the linear relation found between them. It can be said that the variants employed did not produce an exceptional impact in the resulting estimations nor it distorted the linear relation between wind speed and wind power. In fact, the performance of each one of the tested variants depended directly on the ability of the downscaling to reproduce the variability of the observed wind power series.

In addition and similarly to the case of the wind speed, there are some interesting questions related to the long term variability of the wind power production, as for instance, whether they, wind speed and power production maintain the linear relation at monthly time scales. What can be said regarding the trends or anomalous periods for this non-climatological variable? In order to obtain some information regarding these issues, a reconstruction of the wind power series has been calculated using the relation found between the predictand at the three wind farms and the large scale circulation during the calibration period (1999-2003). As in the case of the wind, different sources of information for the atmospheric circulation were employed to project the past variability of the wind power in past periods with no longer available power records.

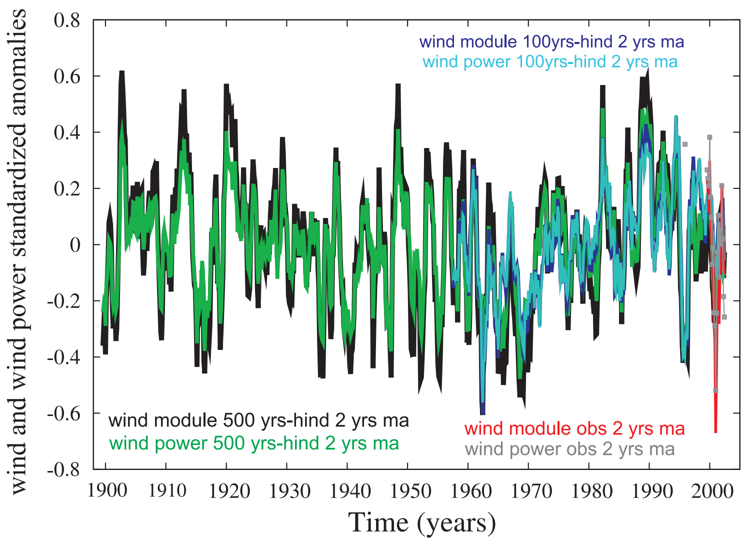

FIG. 5. Regional wind power climatology reconstructed time series. Observations are in red (wind module) and gray (wind power), reconstructions using the ECMWF SLP reanalysis and analysis are in dark blue (wind module) and light blue (wind power). Similarly, reconstructions using as large scale predictor the NCAR/NCEP SLP are in black (wind module) and green (wind production). All the series present a 2 year moving average filter.

The reconstruction, averaged over the three wind farms is represented in Fig. 5. The observed power time series were only extended backward till the beginning of the 20th century, since the calibration period was shorter compared to that of the wind speed. Thus, two different datasets were employed for this aim, the ECMWF reanalysis and analysis ϕ_{850} and $Z_{500-850}$ (1957-2005, light blue in Fig. 5) and the NCAR SLP (from 1899 to 2005) in green. Although it seems that to some degree the reconstruction from the ECMWF datasets presents lower variance than that from NCAR dataset, there is a general good agreement between both reconstructions and between the reconstructions and the observations (in gray) in the overlapping period. Additionally, the comparable reconstructions for the wind speed are represented in Fig. 5. All the series are standardized to allow for a better comparison. It is evident from the graph that the linearity between both variables is maintained along the whole reconstruction period (correlation values are 0.85 and 0.95 for the longer and shorter reconstructions, respectively). Both reveal no overall trends during the 100 year period of reconstruction, although a slight tendency to increased power production is apparent between 1960 and 1990 approximately, in agreement with what was observed in the wind components reconstruction in the previous section (see Fig. 4). As in that case, interesting intra and interannual can be appreciated from Fig. 5. This type of exercise allows for understanding the variability of the wind power production at a certain region at longer timescales. Typically, only one year of observations is required to evaluate whether or not a specific location is suitable for exploiting the wind energy resource. However, nor a single year nor a few of them can offer sufficient information to make the decision of installing a wind farm since the natural variability of the source can be large as evidenced and consequently the production projected could change significantly from one year to other.

3. Conclusions, future work and collaboration between both institutes and publications

The analysis of the wind field variability and predictability at the northern Iberian Peninsula is undertaken by applying a statistical downscaling technique to identify the main associations between the regional predictand and the large scale circulation over the North Atlantic area at monthly time scales. The coherent modes of variability found highlight the strong influence of the topography in the region in the regional wind circulation. The wind field is represented as a linear combination of the leading synoptic patterns governing the regional flow. The approach has proven skillful after comparison of observations and estimations during the validation step.

The methodological variance has been evaluated by carrying out multiple experiments in which different parameters in the model are systematically combined and varied yielding a very large number of estimates. The uncertainty that is associated to this part of the analysis remains in the range of variability of the observations. A full assessment of the uncertainty is provided by considering the impact in estimations of using different data sources as large scale predictors. The results are illustrative of a discrete influence of this type of uncertainty showing the largest influence in the upper deciles of the estimates distribution. Thus, the method applied appeared as a robust approach to estimate the monthly wind in this region.

The long term variability of the regional wind has been assessed by a regression-based approach fed with the information from the large scale circulation in the absence of observed measurements out of the calibration period. No over all trends along the aprox. 350 years wind reconstruction period, though some signs of intra and interannual variability were found. Uncertainties were also projected backward to gain an insight into the potential impact of using different datasets as synoptic circulation predictors.

As a climate-impact-oriented analysis, an insight in the relation of the wind power produced in the region for a period of 5 years (1999-2003) and the large scale circulation was provided. Evidences of synoptic circulations governing monthly variations of the wind power production were found. This allowed for the application of simple strategies to assess the spatial and temporal variability of the wind power over the region under study.

The visit was extremely productive although not long enough to accomplished all tasks proposed. In the next months the two institutes will collaborate in the evaluation of wind predictions based on future simulations from general circulation models for the 21^{st} century together with the corresponding uncertainty projection associated with the downscaling step and that corresponding to the use of several global model simulations in various future emission scenarios.

In the view of the results it is reasonable and interesting to explore potential applications of the methodologies applied in different regions of the Mediterranean together with a similar analysis of the wind field and potential wind power resource variability in future steps of the work.

This study will give rise to a paper that proximately will be submitted to a peer reviewed journal. The next phase described in the previous paragraph can be also the focus of another publication in the following months.

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Reservierung

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27.04	12:34	**MUENCHEN HBF**	->	**ZUERICH HB**	27.04	16:44	2

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27.04	17:00	**ZUERICH HB**	->	**BERN**	0.00	17:57	2

ZUG 832 EC/IC WAGEN 5 Sitzplatz 172

Großraumwagen
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