Wind power:

Exploratory space-time analysis with

M. P. Muñoz* , J. A. Sànchez*, M. Gasulla*, M. D. Márquez**

*Department Statistics and Operations Research (UPC)

** Department of Economics and Economic History (UAB)

(pilar.munyoz@upc.edu)

Outline

1. Introduction & Objectives
2. Exploratory Data Analysis
3. ECF: Empirical-Correlation Function
4. EOF: Empirical Orthogonal Function
5. Conclusions

Motivation

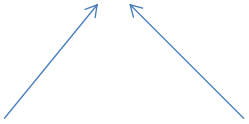
- Knowing the **speed** and **wind direction** and its evolution is very important in **wind generation planning**
- **Statistical models** suitable for **generation planning** take into account the **space time components** of the **wind**,
- These **components** are **highly related** to each other and to other **meteorological variables**

Wind power: exploratory space-time analysis with R
1. Introduction & Objectives 2. Exploratory Data Analysis 3. ECF 4. EOF 5. Conclusions

Evolution of speed and wind direction

Statistical models:
Space time components of the wind

Wind generation planning

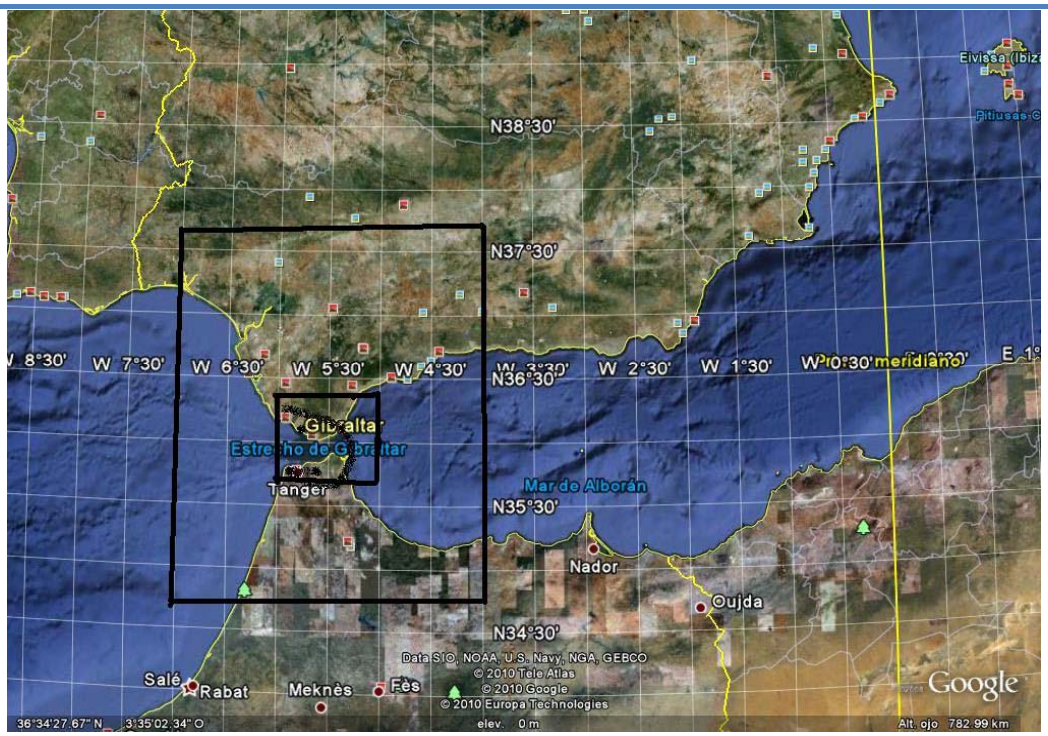


Pressure Temperature

Objectives

- Visualize the **spatiotemporal relationships** between the variables involved in the problem using the **functions we have programmed in R** as well as **other functions** already **implemented in R libraries**

- **Descriptive techniques:**
  - graphical representations **of speed** and **wind direction**
  - **correlation** between different space-time variable
  - **autocorrelation functions** implemented in several space and time lags
  - **EOF**: empirical orthogonal functions
- . . .



Data description:

Data from **Hirlam model**

Period	01/01/2009 to 31/12/2009
Frequency	3 hours
Missing data	01/06/2009 and 02/06/2009
Temporal reference system	UTC(~ GMT)
Modeling	Daily Analysis at 00:00 and forecasting at 3, 6, 9, 12, 15, 18, and 21 hours
Coordinates	LON = W4º30' : W6º30' LAT = N35º3' : N36º5'

Wind power: exploratory space-time analysis with R
1. Introduction & Objectives | 2. Exploratory Data Analysis | 3. CCF | 4. EOF | 5. Conclusions

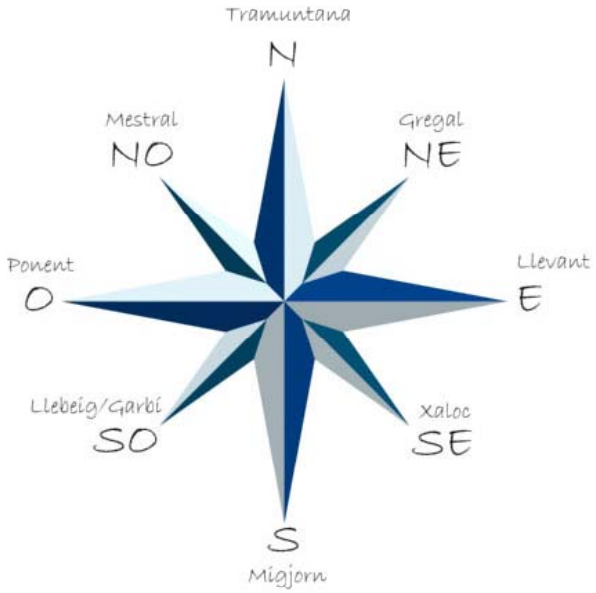
Data description:

North Component (315º-45º)

East Component (45º-135º)

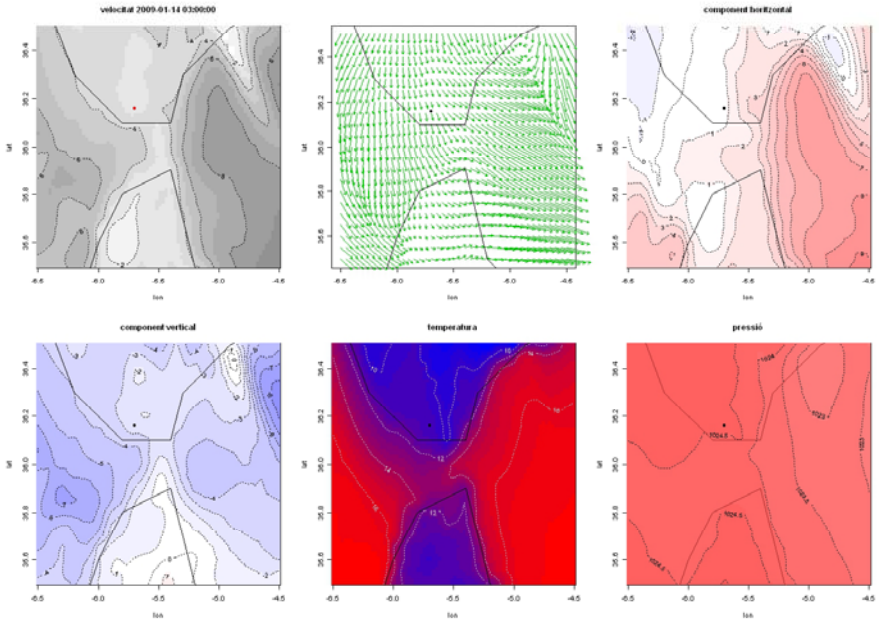
South Component (135º-225º)

West Component (225º-315º)



http://www.amarre.com/html/meteorologia/rosa/index.php

R packages:akima, fields and maps

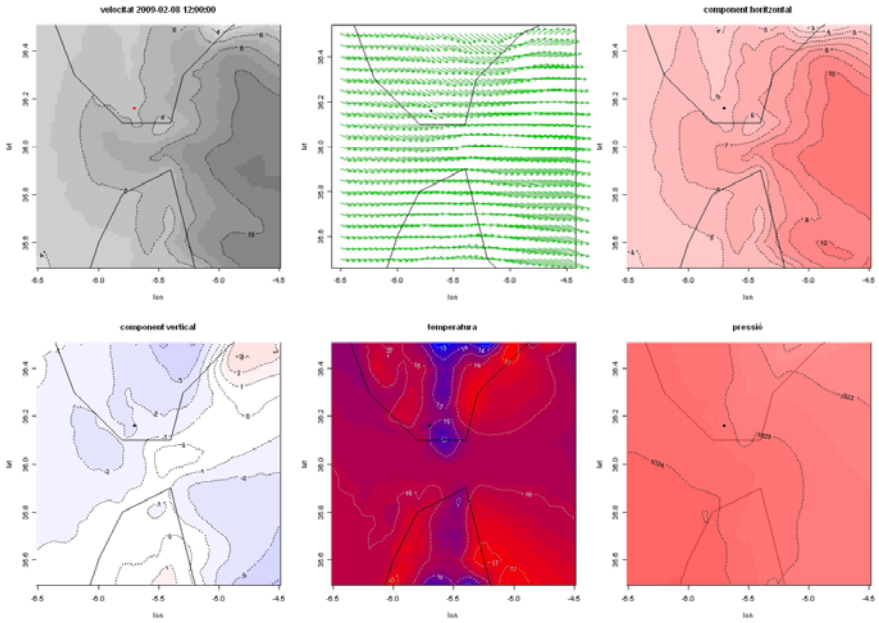


Wind speed, Temperature and Pressure 3.00h 2009/01/14

Wind power: exploratory space-time analysis with R

1. Introduction & Objectives 2. Exploratory Data Analysis 3. ECF 4. EOF 5. Conclusions

R packages:akima, fields and maps



Wind speed, Temperature and Pressure 12.00h 2009/02/08

Marginal plots: *Space (1-D)/Time Plots*[1]

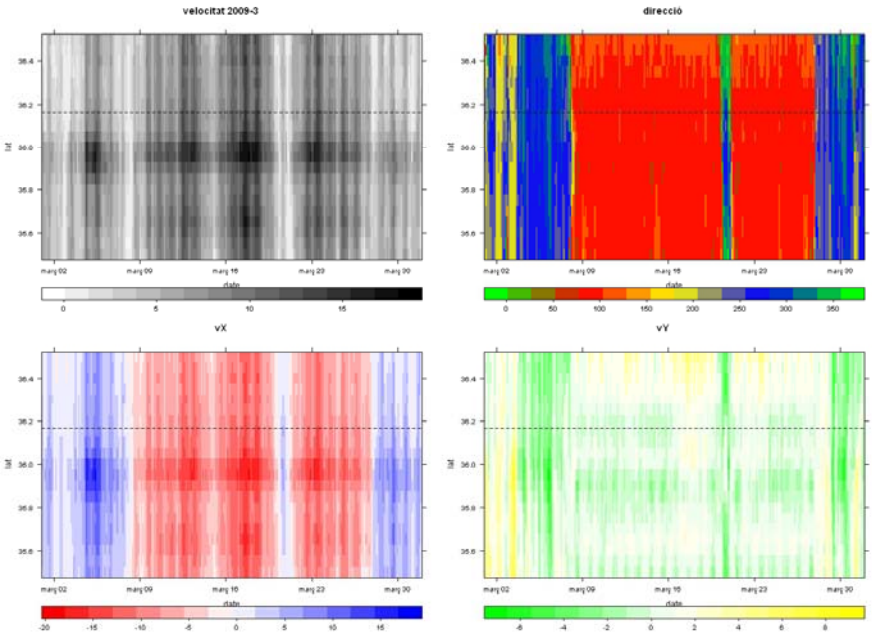
- Method for illustrating the **wave propagation** of climate variables. For example, **wind**, **temperature**, …
- **Bidimensional plot** : x-axis contains time; y-axis represents latitude or longitude
- They help to find **patterns**, **anomalies**, …
- **Visual evidence** of climate variable behavior

[1]Cressie, N., Wikle, C.K. 2011. Statistics for Spatio-Temporal Data. Wiley

Wind power: exploratory space-time analysis with R

1. Introduction & Objectives | 2. Exploratory Data Analysis | 3. ECF | 4. EOF | 5. Conclusions

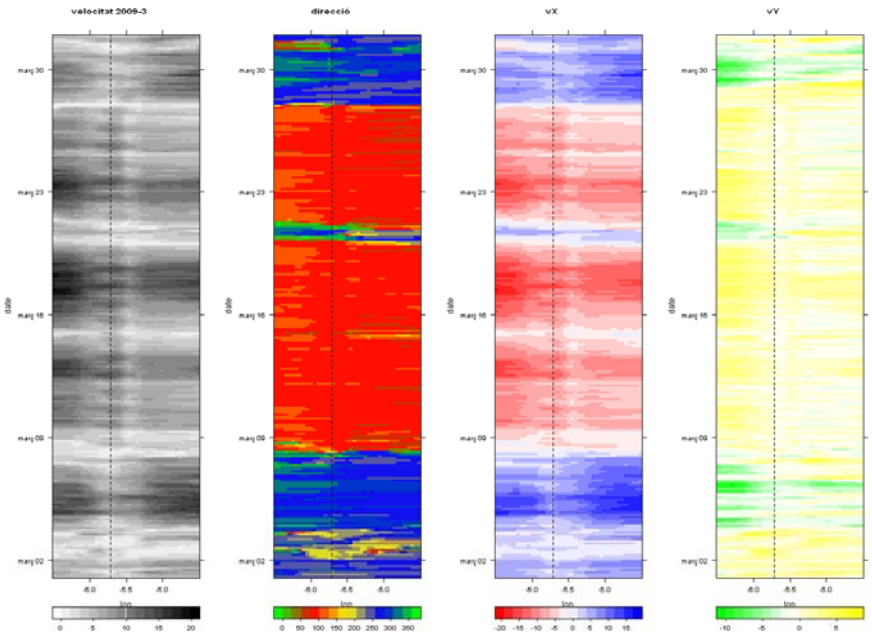
R code: Our implementation



Wind:

From March 9 to Mach 29 2009, **wind direction** (lat) ranged around **100º C**: **East wind** (Levante)

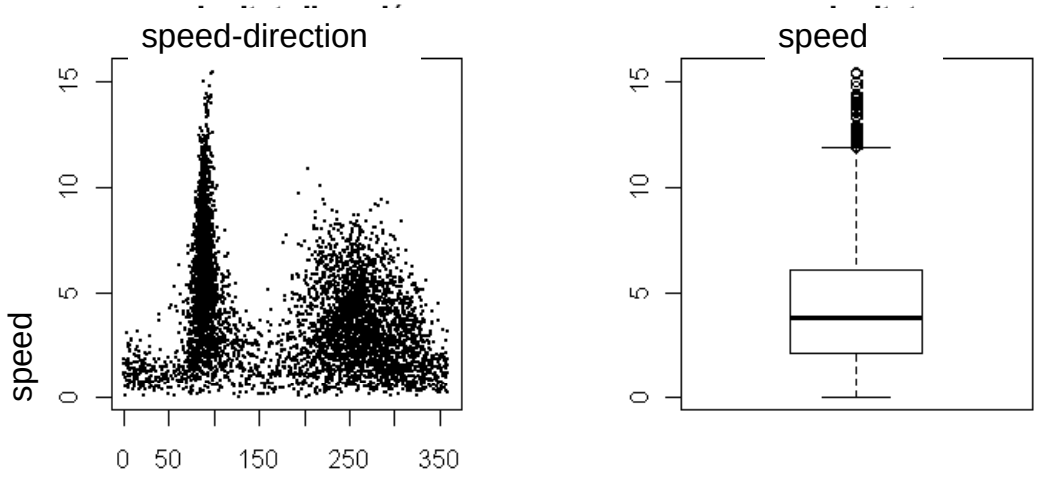
R code: Our implementation



Wind:

From March 9 to March 29 2009, **wind direction** (lon) ranged around **100º C**: **East wind** (Levante)

R code: Our implementation

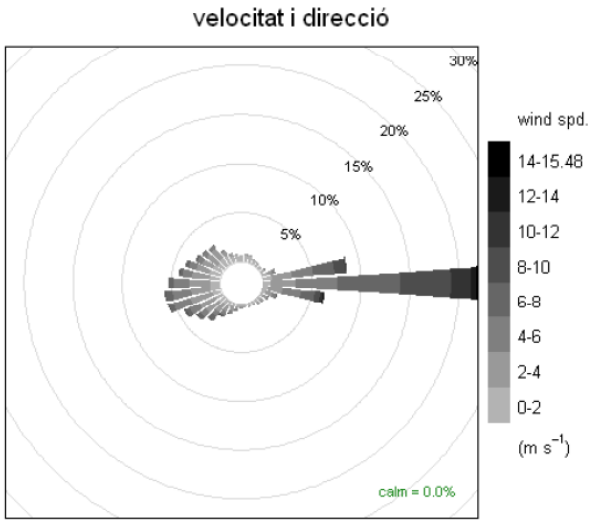


Wind (yearly)

Highest wind speeds when the **wind direction** ranges around **100º C**: **East wind** (Levante)

Speed and direction

R package: WindRose



The same conclusion as in the previous slide

Empirical Correlation Function[1]

- Procedure for **detecting spatio-temporal correlations** between of climate variables as for example **wind**
- It is convenient to **present graphically** these matrices
- The space-time observations are

  $Z_t = (Z(s_1,t),\cdots,Z(s_m,t))'$ Where ***s*** is for space and ***t*** for time
- The empirical lag-τ **spatial covariance matrix** is

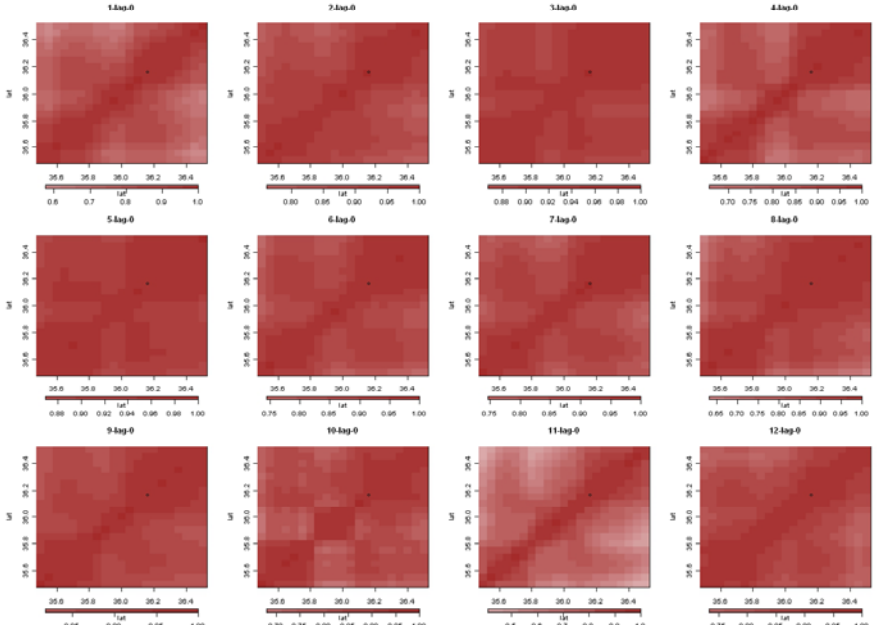
$$\hat{C}_Z^{(\tau)} = \frac{1}{T-\tau}\sum_{t=\tau+1}^{T}(Z_t-\hat{\mu}_Z)(Z_{t-\tau}-\hat{\mu}_Z)', \quad \tau = 0,1,\cdots,T-1$$

  Where the empirical **spatial mean** is $\hat{\mu}_Z = \frac{1}{T}\sum_{t=1}^{T} Z_t$
- The empirical lag-τ **spatial correlation matrix** is

$$\hat{R}_Z^{(\tau)} = \hat{D}_Z^{-1/2}\hat{C}_Z^{(\tau)}\hat{D}_Z^{-1/2} \quad \text{and} \quad \hat{D}_Z = diag(\hat{C}_Z^{(0)})$$

[1]Cressie, N., Wikle, C.K. 2011. Statistics for Spatio-Temporal Data. Wiley

R our: Own implementation

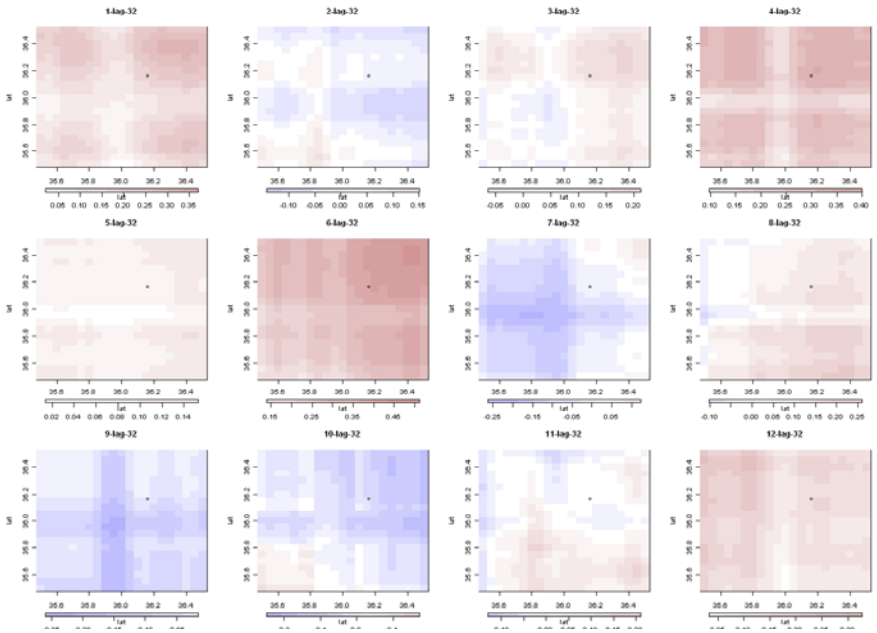


Empirical correlation (lat) at lag 0, for the twelve months

Wind power: exploratory space-time analysis with R

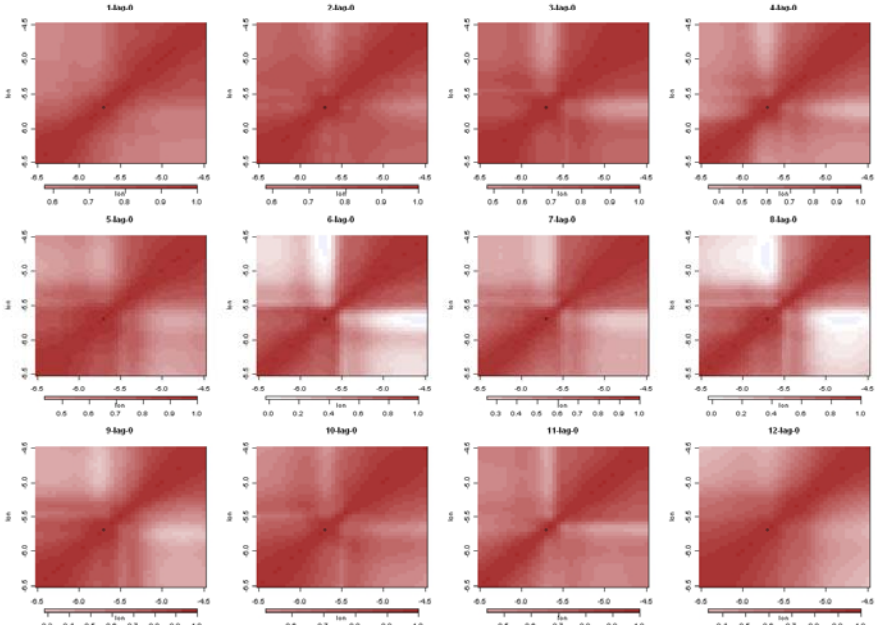
1. Introduction & Objectives 2. Exploratory Data Analysis 3. ECF 4. EOF 5. Conclusions

R code: Our implementation



Empirical correlation (lat) at lag 32, for the twelve months

R code: Our implementation

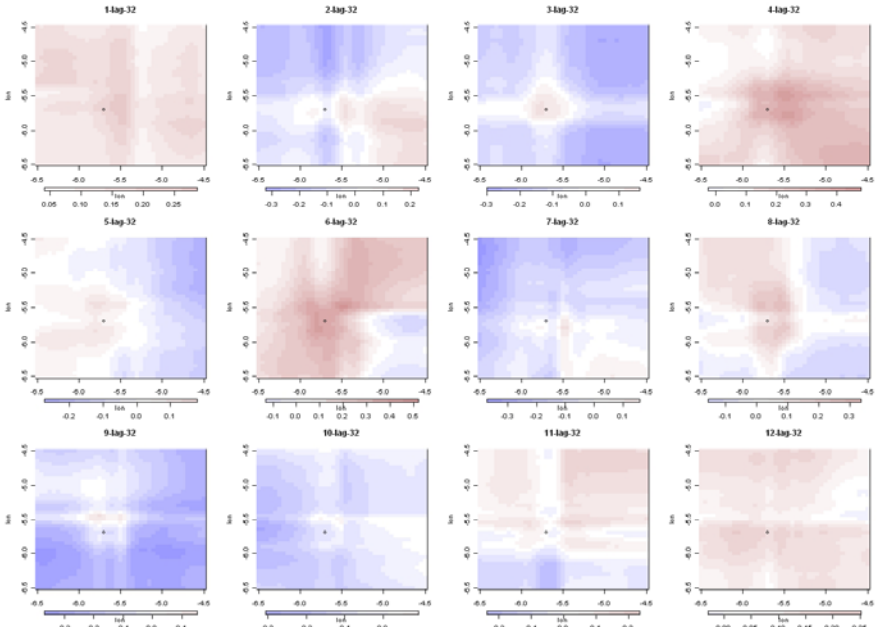


Empirical correlation (lon) at lag 0, for the twelve months

Wind power: exploratory space-time analysis with R

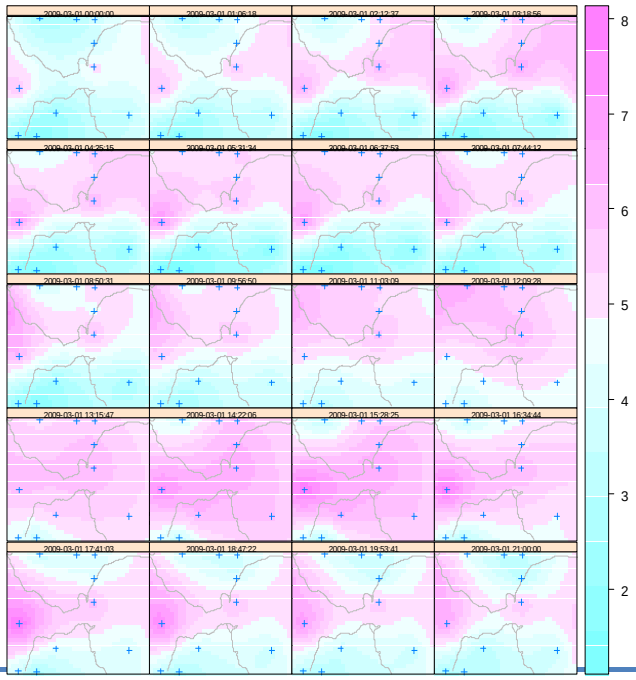
1. Introduction & Objectives 2. Exploratory Data Analysis 3. ECF 4. EOF 5. Conclusions

R code: Our implementation



Empirical correlation (lon) at lag 32, for the twelve months

Spatio-temporal Kriging



R packages: sp, mapdata, maps, maptools, rgdal, xts, gstat, spacetime

- Procedure for **space-time interpolation** from a sample (**x** in the plot)
- Variable: **wind speed**
- **Date**: 2009/03/01.
- **Hours**: 20 hours, starting at 0:00 and finishing at 21:00

EOF: Empirical Orthogonal Function

- **EOF** is the "geophysicist's terminology for the **eigenvectors** in the classical eigenvalue/eigenvector decomposition of **a covariance matrix**"[1,2]

- Reduce the **dimensionality** (space or time component) in a large **spatio-temporal data set**.

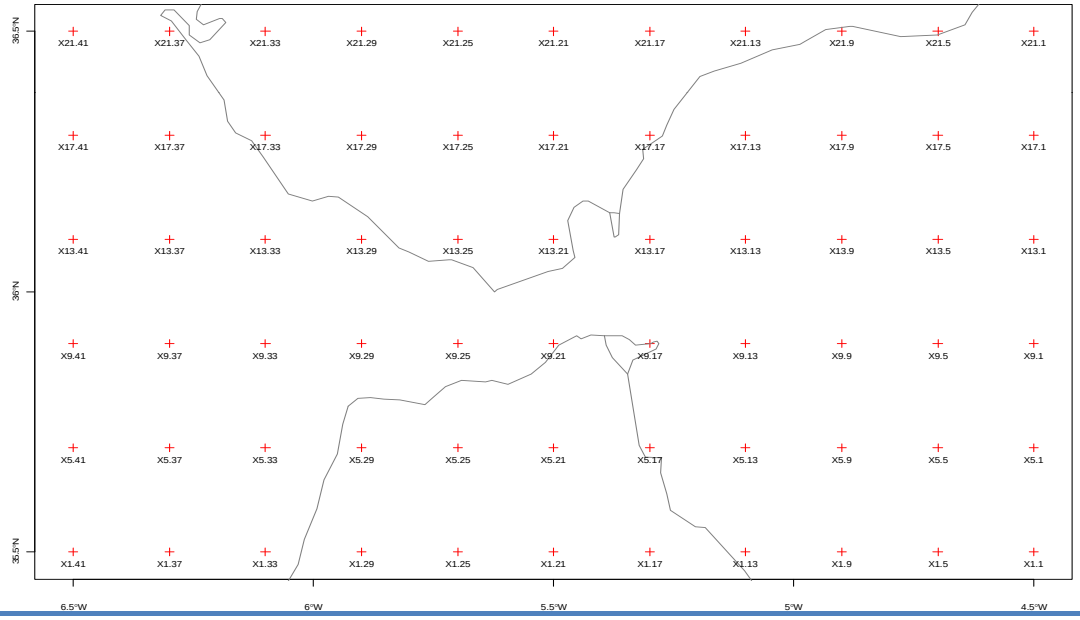
- EOF **identifies structures** in the **space dimension**[3]

- Useful to **forecast space-time superficies** as for example **wind** or **sea surface temperatures**

[1]Cressie, N., Wikle, C.K. 2011. Statistics for Spatio-Temporal Data. Wiley
[2]Pebesma, E. 2011. Classes and methods for spatio-temporal data in R: the *spacetime* package (cran.r-project.org)
[3]Le,N.D., Zidek, J.V. 2006. Statistical analysis of environmental space-time processes. Springer

EOF applied to wind speed

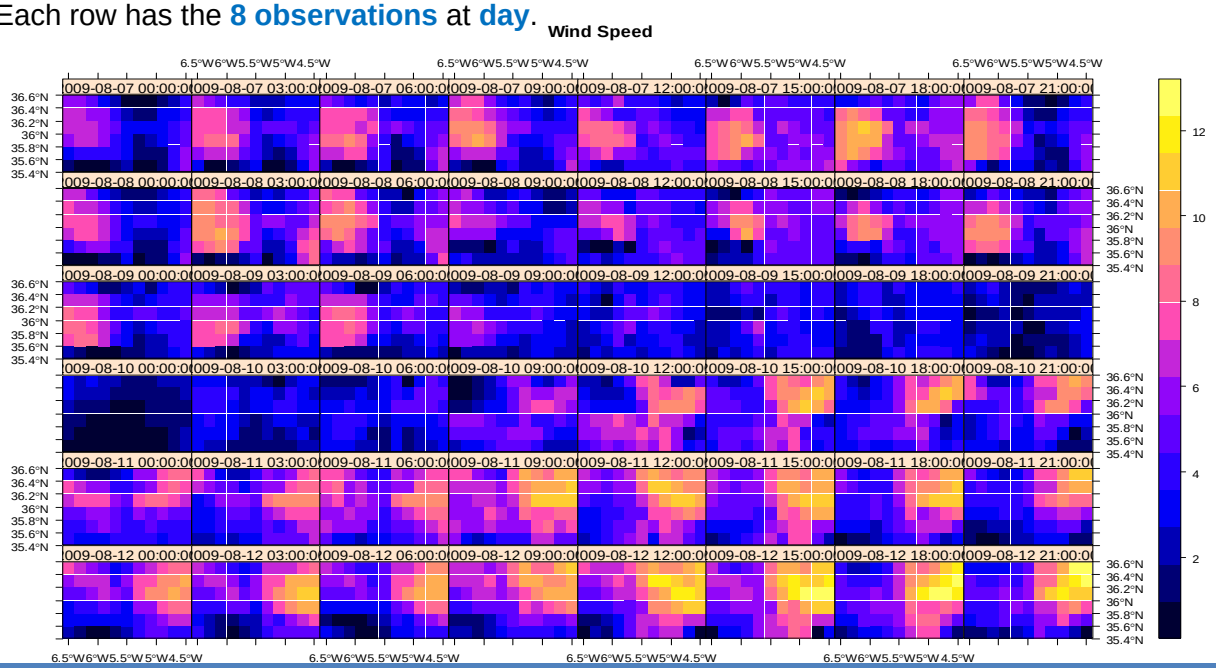
66 time series (one in each point), **observations** every **3 hours** for **2 years**



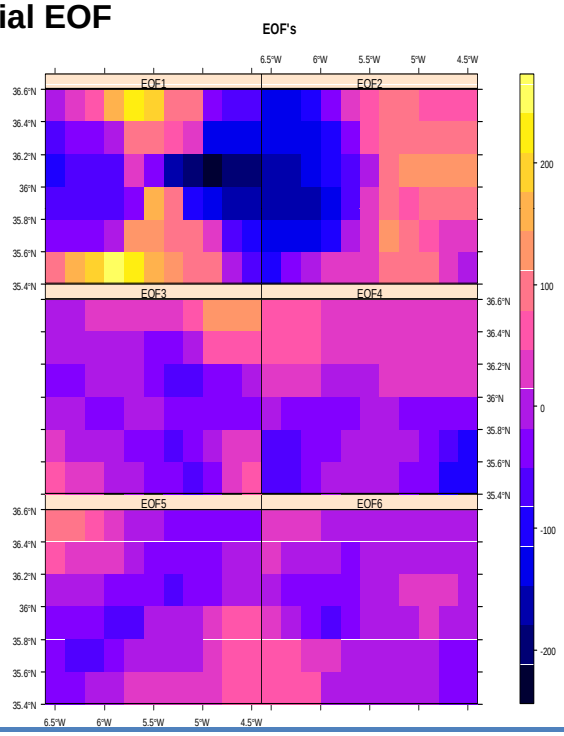
Wind power: exploratory space-time analysis with R

1. Introduction & Objectives 2. Exploratory Data Analysis 3. CCF 4. EOF 5. Conclusions

This **plot** shows the **wind speed at 66 points** during **6 days** (from Aug/07/2009 to Aug/12/2009).
Each row has the **8 observations** at **day**.



Spatial EOF

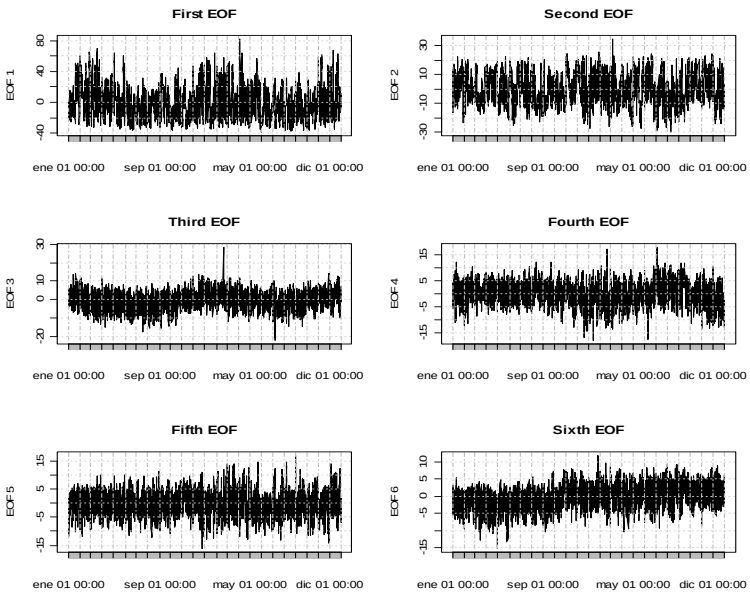


- The **first six EOF**
- **The first component** clearly separates **land / sea** and the **second west / east**

Wind power: exploratory space-time analysis with R

1. Introduction & Objectives 2. Exploratory Data Analysis 3. CCF 4. EOF 5. Conclusions

Temporal EOF



Conclusions

- **The relationships detected** by the exploratory space time analysis are very useful in the statistical models, obtaining more accurate models

- The **forecast** of future **wind values** will be **more accurate**.

- The **accuracy** achieved in predicting **wind speed** and **direction** will have **a positive impact** on the **quality** of **wind generation forecasts**.

- The presented **techniques** will be useful for **diagnosing the quality of fit** for the estimated models.

Wind power: exploratory space-time analysis with R

1. Introduction & Objectives 2. Exploratory Data Analysis 3. CCF 4. EOF 5. Conclusions