P 1.31 DETERMINING TEMPERATURE LAPSE RATES OVER MOUNTAIN SLOPES USING MODIFIED GWR IN THE PYRENEES AREA

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1. INTRODUCTION

The Pyrenees range extents longitudinally 435 km, from Biscay Gulf in the Atlantic Ocean to the Mediterranean Sea, of which 220 km belong to Catalonia in the eastern area where the study takes place. Pyrenees separate the Iberian Peninsula from the rest of Europe, supposing a barrier to advections, especially those from the north. High peaks and deep u-shaped glacial valleys within the range cause typical mountain meteorological phenomenon such as temperature inversions, foehn effect, extremely wind chill, etc. (Barry, 1999) which are not detected by Numerical Weather Prediction (NWP).

Two specific valleys in Catalonia have been chosen (Figure 1.1), La Val d'Aran and La Cerdanya, where mountains arise 3000 meters from valleys 600 meters above sea level.

Both valleys have meteorological and climatological characteristics which make them different from other valleys and despite the distance between each other is around 100 km, these differences between La Val d'Aran and La Cerdanya are also remarkable.

Due to its orientation La Val d'Aran has Atlantic influence and north advections are frequent, especially in winter, with barrier clouds and persistent precipitations.

On the other hand, La Cerdanya is more influenced by the Mediterranean Sea and its main characteristics are the strong temperature inversions (Pepin, 2006) in winter season when high pressures and stability are settled over the south-west Europe and cold air pools are likely to be formed. Thus, the Automatic Weather Station (AWS) of Das in La Cerdanya is the unique settled below 2000 meters that has registered the lowest temperature value since 1996 (-22.6ºC in December 2001). Several studies (Gustavsson, Karlsson, Bogren and Lindqvist, 1997; Iijima and Shinoda, 2000; Clements, Whiteman and Horel, 2002) mention this valley phenomenon which appears in other countries and continents like in La Cerdanya.

Although temperature inversions also occur in La Val d'Aran, these are not as frequent and strong as in La Cerdanya are under the same synoptic situation. The different shape of the valleys can explain the different temperatures existing between these ones (Müller and Whiteman, 1988).

Due to these local differences and the difficulty to detect them by NWP it has been thought to develop a downscaling method in order to detect these local peculiarities.

Firstly it was thought to use a higher resolution NWP, but the computation time needed was too large and we decided to use regression combined with Geographically Weighted Regression in order to achieve a good representation of the local phenomenon existing there, the temperature inversions.

Figure 1.1. a) Catalonia in Europe. b) Catalan Pyrenees: situation of the two valleys studied (Left circle: Val d'Aran. Right circle: La Cerdanya)

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2. DATA

2.1 *Location*

In order to obtain the vertical temperature profiles two AWS have been chosen with some location conditions. AWS must be located in the same valley, at least one in the valley floor and the other one on the mountain slope or top.

AWSs located in Val d'Aran and La Cerdanya carry out these conditions (Figure 2.1). Some of them are located on the mountain slopes, 2000 meters above sea level (Sasseuba, Bonaigua, Malniu and Cadí Nord) and others on the valley floor (Vielha and Das). Moreover, AWS in both valleys are distributed and located in similar heights, making them comparables.

2.2 *Data types*

Three types of data have been used:
- Radiosonde data
- AWS data
- NWP data

From radiosonde, temperature data has been obtained. The data has been provided by nearby radiosonde stations (Figure 2.2) such as Bordeaux/Merignac (BDX-07510) and Nîmes/Courbessac (NIM-07645) in France, Zaragoza (ZGZ-08160), Barcelona (BCN-08190) and Palma de Mallorca (PMA-08301) in Spain, and from each one, temperature data at 00Z in the same elevation than AWS.
It was thought that values from radiosonde could be similar or close to those from mountain stations, in this case within the Pyrenees range (Pepin, 2004). In particular AWS temperatures are comparables with the inside domain of vertical structure interpolation.

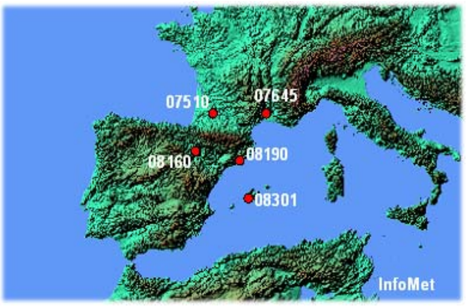

Figure 2.2. Radiosonde stations code and location

Surface temperature data from AWS correspond to 06Z. The high-elevation sites are Sasseuba (2226 m) and Bonaigua (2266 m) in La Val d'Aran and Malniu (2310 m) and Cadí (2149 m) in La Cerdanya. Lower sites are Vielha (1000 m) in La Val d'Aran and Das (1097 m) in La Cerdanya.
All these stations are equipped with temperature sensors Vaisala HMP45A, placed 4 meters high on high elevation sites and 1,5 meters high on the others.

NWP data are provided by MM5 model, a non-hydrostatic with primitive equations model using terrain following coordinates (Grell *et Al.* 1995) developed at PSU/NCAR.
MM5 12km domain has been used in this study (grid size: 70X70X30; convection: Grell; microphysics: Schultz; boundary layer parameterization: MRF/RRTM).
Specifically from the model for each site, next data has been provided:
- Surface temperature provided by the lowest model level (analysis)
- 2 meters temperature forecast: 00Z (24 hours forecast) and 06Z (6 hours forecast)
- Vertical temperature profiles forecasts at 06Z for each radiosonde station (BDX, NIM, ZGZ, BCN and PMA)
- Dew-point temperature (Td): 00 and 06Z (24 hours and 6 hours forecast respectively)

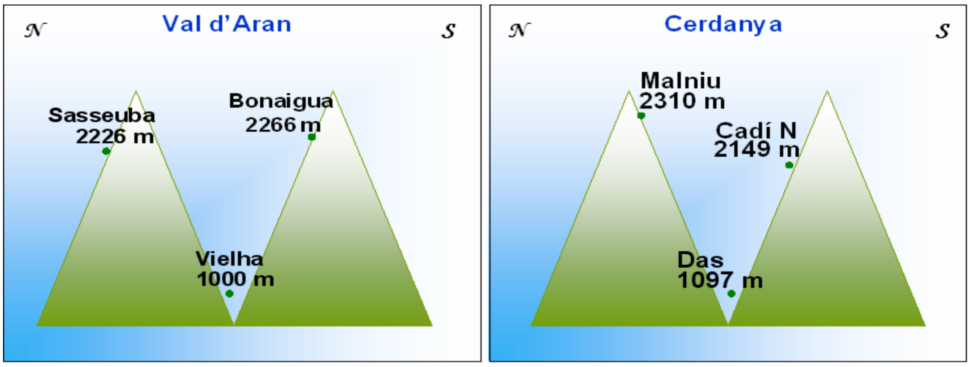

Figure 2.1. Scheme of AWS distribution in each study valley.

2.3 *Period of study*

Data period extents from 1st November 2007 to 31st March 2008.
Although this is a short period of time, results achieved during the 2007/2008 winter season let us foresee success when applying method with longer temporal data series.
Winter data has been chosen due the misleading accuracy shown by the model when determining temperature (Sairouni *et al.,*2007) specially at lower levels because models do not simulate correctly the interaction zone between atmosphere and mountains (Quiby and Schubiger, 2002).

3. METHODOLOGY

3.1 *Constructing regressions*

Determining predictors

Prior the construction of regressions all multilinear correlation coefficients have been obtained to see the behaviour of each site. In order to obtain the appropriate variables for their regressions, stepwise method (Wilks, 1995) has been applied.

However, when working with Geographically Weighted Regression (GWR), the same independent variables must be either used in high-level sites or low-level sites.

Initial data for each site in both valleys have been:

- MM5 temperature forecast at 06Z (T_MM5)
- MM5 dew-point temperature forecast at 06Z (Td_MM5)
- MM5 radiosonde temperature forecast for Barcelona (T_BCN), Bordeaux (T_BDX), Palma (T_PMA), Nîmes (T_NIM) and Zaragoza (T_ZGZ) interpolated at the same height of the sites.

In la Val d'Aran T_MM5 and T_PMA have been selected when applying stepwise method (Table 3.1) and appear in all cases. Otherwise, in Vielha Td_MM5 is as important as T_BDX in high-elevation sites. As told, homogeneity of independent variables is needed in GWR and therefore the selected variables to construct regressions for the sites in La Val d'Aran have been T_MM5, Td_MM5, T_BDX and T_PMA.

On the other hand, the selected variables in La Cerdanya have been T_MM5, Td_MM5, T_BDX and T_BCN (Table 3.2). In this case, T_BDX appears every time that stepwise is applied in each site. Although T_MM5 and Td_MM5 do not appear in Cadí Nord but it is important in Das, then the use of these variable in the regression have been considered. Another selected variable has been T_BCN even though it is only important in Cadí Nord. But changing T_NIM and T_ZGZ for T_BCN in Malniu, insignificant differences have been obtained and at least T_BCN is a radiosonde station near La Cerdanya.

	T_MM5	Td_MM5	T_BCN	T_BDX	T_PMA	T_NIM	T_ZGZ
Bonaigua	X			X	X		
Sasseuba	X	X		X	X		
Vielha	X	X	X		X		

Table 3.1. Different variables selected using stepwise for La Val d'Aran.

	T_MM5	Td_MM5	T_BCN	T_BDX	T_PMA	T_NIM	T_ZGZ
Cadí Nord			X	X			
Malniu	X	X		X		X	X
Das	X	X		X			

Table 3.2. Different variables selected using stepwise for La Cerdanya.

Regression coefficients

Once the multilinear regression assumptions (linearity, independence, homocedasticity, normality and non-collinearity) have been checked successfully the regressions coefficients have been calculated for both valleys.

For each site in La Val d'Aran the regression coefficients and correlation (Table 3.3) are obtained.

These coefficients are normally well conditioned but in some cases appears the under significance problem because of having chosen the same independent variables for high and low sites.

The same proceeding has been carried out with data from sites in La Cerdanya and the regression coefficients are shown in table 3.4.

	Vielha	Bonaigua	Sasseuba
Constant	2.293	-1.030	-2.060
T_MM5	0.402	-0.087	0.833
Td_MM5	0.314	0.736	-0.225
T_BDX	-0.028	0.284	0.424
T_PMA	0.221	0.298	0.277
R^2	0.725	0.882	0.884

Table 3.3. Regression coefficients and correlation (blue shadowed) in La Val d'Aran

	Das	Malniu	Cadí N
Constant	1.792	-0.168	-1.207
T_MM5	0.533	0.655	0.137
Td_MM5	0.462	-0.111	-0.028
T_BDX	-0.501	0.435	0.325
T_BCN	0.093	0.285	0.732
R^2	**0.430**	0.911	0.932

Table 3.4. Regression coefficients and correlation (blue shadowed) in La Cerdanya

3.2 *Geographically Weighted Regression*

The aim of developing a modified Geographically Weighted Regression (GWR) is to obtain temperature values at different sites over the slope between known mountain and floor-valley sites from which their equation regressions have been calculated. GWR is a method which permits to identify the spatial heterogeneity of regression models when spread georeferenced data is used.

The challenge using this method is to calculate the freezing level in low levels, under 2000 meters high (6600 feet) where NWP does not work as it would be expected despite representing small domains (12 or 4 km).

The main hypothesis to construct the GWR is the expected continuity of the regression coefficients in a neighbourhood of each regression point. Then it is possible to construct regressions in these neighbourhoods that will be more similar in closer points than in those obtained when moving away from the point. Therefore the GWR could be used as interpolation method constructing the regression equations for intermediate points.

Despite the GWR is used normally as horizontal interpolation (Lookingbill, 2002), in this case it has been used as a vertical interpolation among a point located in a lower site and another higher in order to calculate the vertical temperature profile.

This model is suitable for the problem that concerns this study because the temperature behaviour has notable differences between the valley floor and mountain and it is expected that points closer to each one will have similar characteristics.

Formally expressed, the GWR model is

$$y_i = \beta_{i0} + \sum_{k=1}^{p} \beta_{ik} x_{ik} + \varepsilon_i \qquad i = 1,\ldots,n$$

where the dependent variable is y_i in the i position, x_{ik} is the kth independent variable in the i position, β_{ik} is the local regression coefficient for the kth independent variable in the i position, and ε_i is the random residue in the same i position.

For every site the regression coefficients have been estimated. In matricial notation every regression coefficient would be estimated with

$$\hat{\beta}(i) = \left[X^T.W(i).X\right]^{-1} X^T.W(i).y$$

where $W(i) = diag\left[w_1(i),\ldots,w_n(i)\right]$ is the diagonal matrix with the weight values that vary for each position i, X is the matrix of independent variables with the first column filled in with 1 and y is the vector of dependent variables and $\hat{\beta}(i) = \left(\hat{\beta}_{i0}, \hat{\beta}_{i1},\ldots,\beta_{ip}\right)^T$ for each position i.

In order to determine weights, several kernel functions can be used (Fotheringham *et al*. 2002). In this particular case $w_{ij} = \exp\left[-1/2(d_{ij}/b)^2\right]$ has been chosen, where *b* refers to the bandwidth. Adjusting the bandwidth in order to have success in the vertical temperature profiles determination is hard task because there is high sensibility within the bandwidth chosen.

4. RESULTS

4.1 *Regressions*

Observing the RMSE and R^2 (Tables 4.1 and 4.2) of the temperatures for 06Z calculated from different methods (regression and NWP) the best values are those obtained by regression model.

	Bonaigua	Sasseuba	Vielha
MM5 12 km	2.20	2.95	3.99
Regression	1.46	1.56	1.72
MM5 4 km	1.86	4.02	2.61
	Malniu	**Cadí N**	**Das**
MM5 12 km	2.77	2.93	4.17
Regression	1.35	1.15	3.13
MM5 4 km	2.42	2.01	7.32

Table 4.1. RMSE values for each site obtained by different methods

	Bonaigua	Sasseuba	Vielha
MM5 12 km	0.78	0.65	0.62
Regression	0.88	0.88	0.73
MM5 4 km	0.87	0.73	0.43
	Malniu	Cadí N	Das
MM5 12 km	0.72	0.59	0.20
Regression	0.91	0.93	0.43
MM5 4 km	0.84	0.83	0.05

Table 4.2. R^2 values for each site obtained by different methods

When temperature values obtained with regression equations have been compared with the values from AWS, a bias reduction has been observed (Figure 4.1) related to MM5 simulations.

As expected, regression (statistic downscaling) has improved NWP 12 km. It has been thought to reduce MM5 to 4 km resolution (dynamic downscaling) in order to improve all these other methods. However, RMSE and R^2 from MM5 4 km, although the increase in resolution, no improvement has been observed in relation to regression, even in some cases, MM5 4 km domain is worse than 12 km.

4.2 *GWR*

Once the regressions have been done for each site the vertical temperature profile has been calculated between the couple of points Vielha-Bonaigua (GWR1), Vielha-Sasseuba (GWR2), Das-Malniu (GWR3) and Das-Cadí Nord (GWR4).

In order to carry out the GWR it is needed to determine the intermediate points between the couple of sites and the weight's bandwidth. The chosen points are placed at distances greater than 4 km to compare the regression with the numerical model of 4 km. On the other hand, it is difficult to choose the weight bandwidth because it is not possible to get a systematic method to determine it at each valley. Then different configurations have been tried until a suitable result has been obtained.

4.3 *Studied cases and GWR validation*

When a thorough analysis of the regression model behaviour has been necessary, two episodes characterized by temperature inversions either at 06Z or during nocturnal hours have been studied. The main reason for having chosen episodes with temperature inversion has been the difficulty of NWP to detect this phenomenon. The analyzed episodes extend from 31st December 2007 to 4th January 2008 and 1st to 4th March 2008.

Study case 1 (2007/12/31 to 2008/01/04)

This case departs from an anticyclonic situation with surface pressure levels reaching 1028 hPa due to a ridge affecting the whole troposphere, hence strengthening the stability (Figure 4.2). These settled weather conditions facilitate temperature inversions, especially when the sky is clear overnight. This phenomenon is stronger in La Cerdanya than in la Val d'Aran, because of the AWS placement and the valley shape as well.

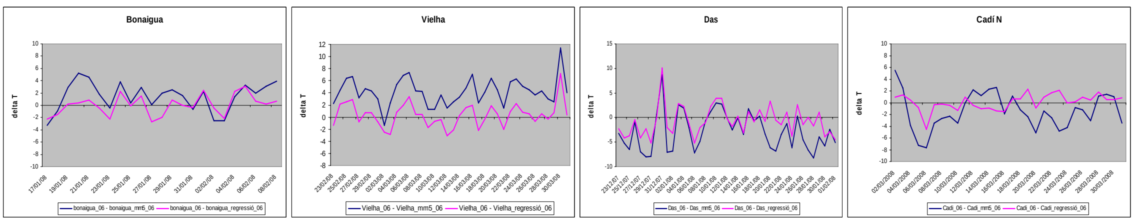

Fig. 4.1. Differences between values from AWS and values from MM5 model (blue colour) and values from regressions (pink colour). Left to right: Bonaigua, Vielha, Das, Cadí N.

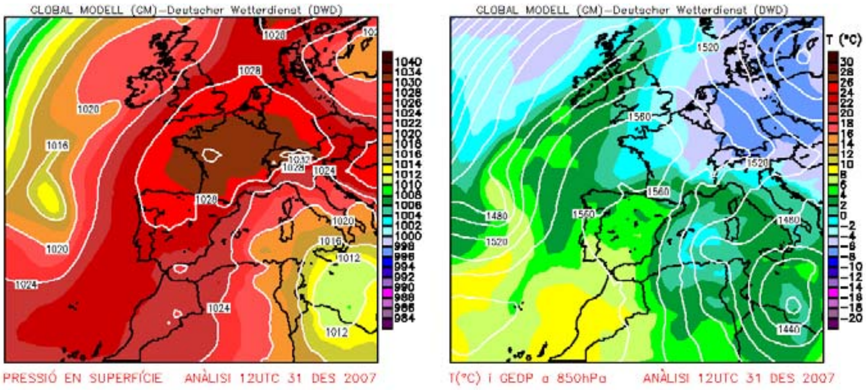

Figure 4.2. Surface chart and 850 hPa topography. 31.12.2007 12Z

To determine the best downscaling method in this case, whether dynamic or statistic, the values from regression and values from NWP have been compared in order to detect the temperature inversions in the topographical profiles used in the GWR (Figure 4.3a & 4.3b).

Values shown from multilinear regression have been able to represent the existing temperature inversions either in topographical profiles in La Val d'Aran and La Cerdanya whereas NWP have not been able to detect this phenomenon.

Despite the worse behaviour of the lower-sites regression shown at Table 4.1 & 4.2, the regression has better skill than mesoscale MM5 model nevertheless its 4 km resolution (Figure 4.3a & 4.3b).

Although the 4 km resolution improves the topography representation used by the 12 km model, this improvement is not enough to detect the inversions properly.

When observing values from GWR for intermediate points (Figure 4.4) coherent behaviour compared with the temperature profiles expected in inversion cases.

NWP in this case has neither been able to represent the real situation because the temperatures of intermediate points vary between the dotted lines on the figures 4.3 (right margin).

The improvement achieved in La Val d'Aran is better than the one achieved in La Cerdanya as can be seen in GWR4 (Figure 4.4) where the intermediate points temperature do not follow the supposed behaviour at the end of the inversion episode. This is caused by the misleading regression of Das that will be studied thoroughly in the future.

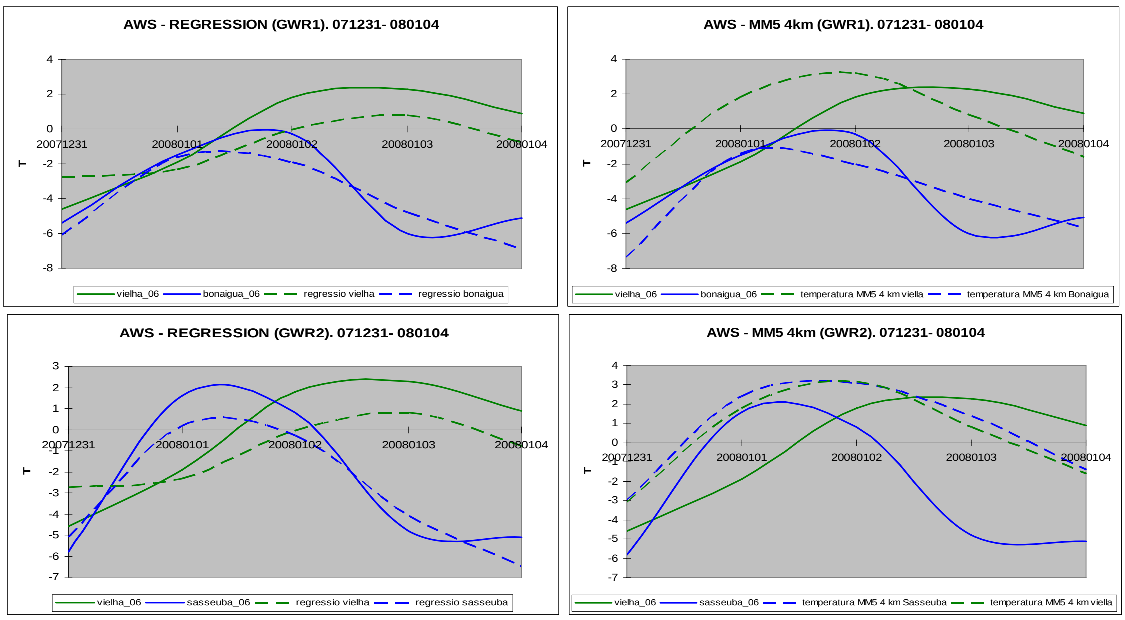

Figure 4.3a. Continuous line shows the temperature evolution at 06Z registered by AWS. Dotted line shows values obtained with the regression model (left graphs) and MM5 4 km (right graphs). GWR1: Vielha (green) – Bonaigua (blue); GWR2: Vielha (green) – Sasseuba (blue).

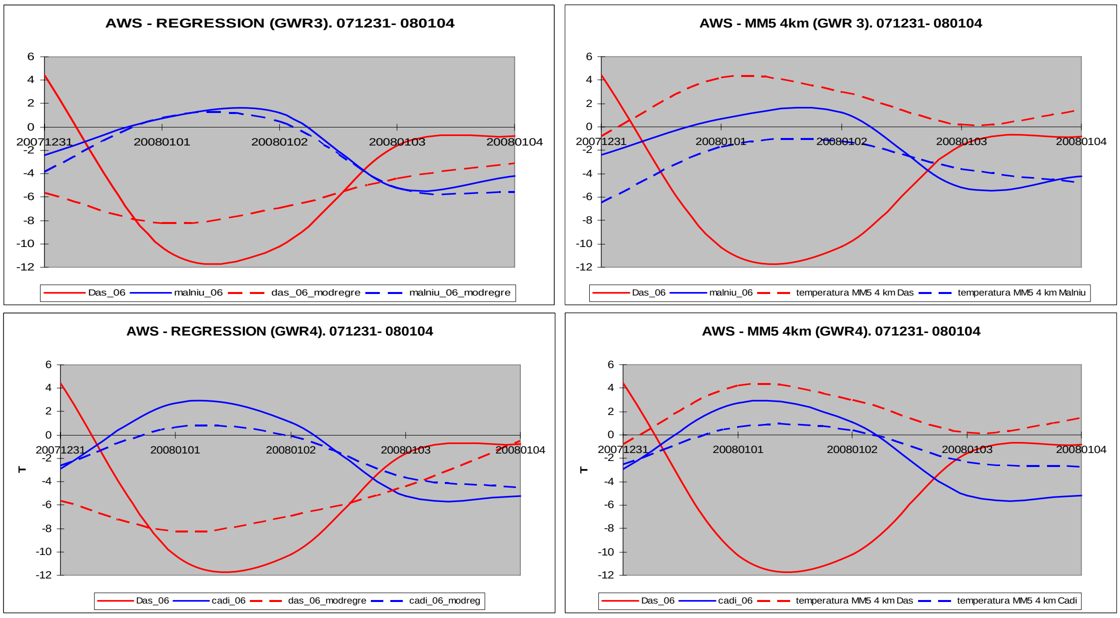

Figure 4.3b. Continuous line shows the temperature evolution at 06Z registered by AWS. Dotted line shows values obtained with the regression model (left graphs) and MM5 4 km (right graphs). GWR3: Das (red) – Malniu (blue); GWR4: Das (red) – Cadí N (blue)

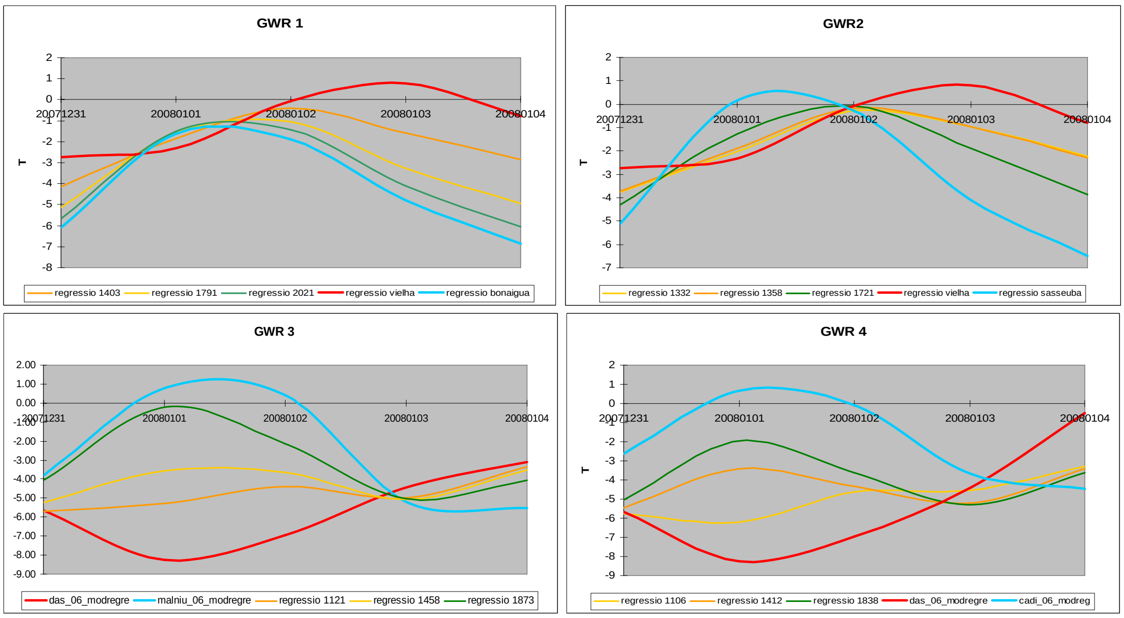

Figure 4.4. Temperatures obtained from GWR regressions across every transversal section in La Val d'Aran (GWR1 & GWR2) and La Cerdanya (GWR3 & GWR4).

<u>Study case 2</u> (2008/03/01 to 2008/03/04)

A dynamic anticyclone is established over the Iberian Peninsula again, hence allowing the temperature inversion to reinforce due to the atmospheric stability (Figure 4.5). At the end of the episode, an advection breaks the inversion recovering the normal temperature profile on the analyzed valleys. As in the first case, the stronger inversion has been detected in La Cerdanya, with a pronounced difference between the floor valley temperatures and the mountain ones.

When regression values and NWP values have been compared with the recorded at the AWS (Figure 4.6), the existent inversion has been detected by regression but not by the model. The finest model resolution is not enough to detect inversions again as regression model has done.

Finally, the GWR analysis has been done (Figure 4.7). It shows that in all the GWR occur the same than in the previous case where it works better in La Val d'Aran than in La Cerdanya due to the misleading regression of Das.

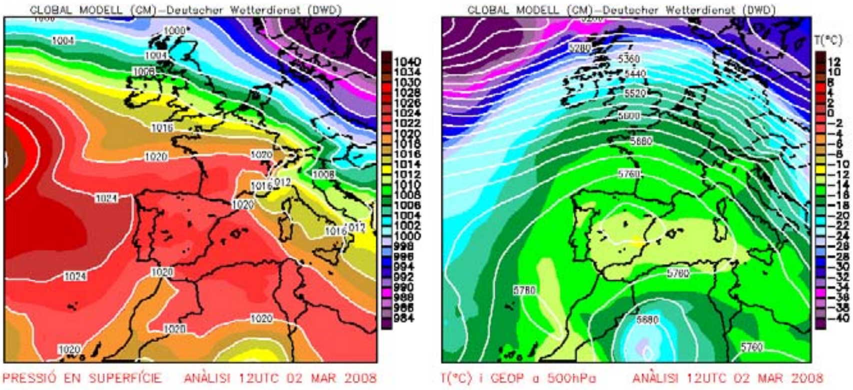

Figure 4.5. Surface chart and 500 hPa topography. 02.03.2008 12Z

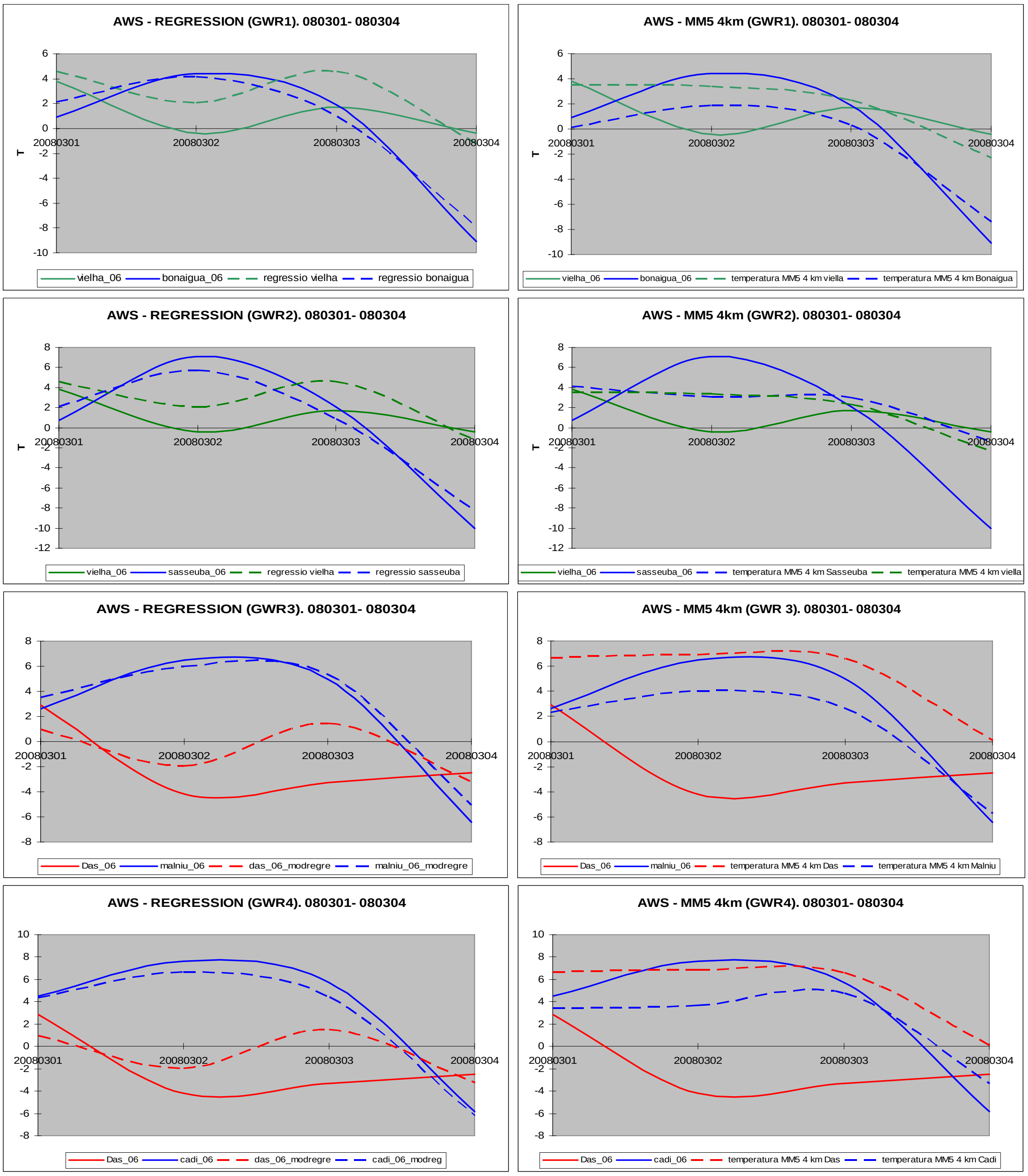

Figure 4.6. Continuous line shows the temperature evolution at 06Z registered by AWS. Dotted line shows values obtained with the regression model (left graphs) and MM5 4 km (right graphs). GWR1: Vielha (green) – Bonaigua (blue); GWR2: Vielha (green) – Sasseuba (blue). GWR3: Das (red) – Malniu (blue); GWR4: Das (red) – Cadí N (blue).

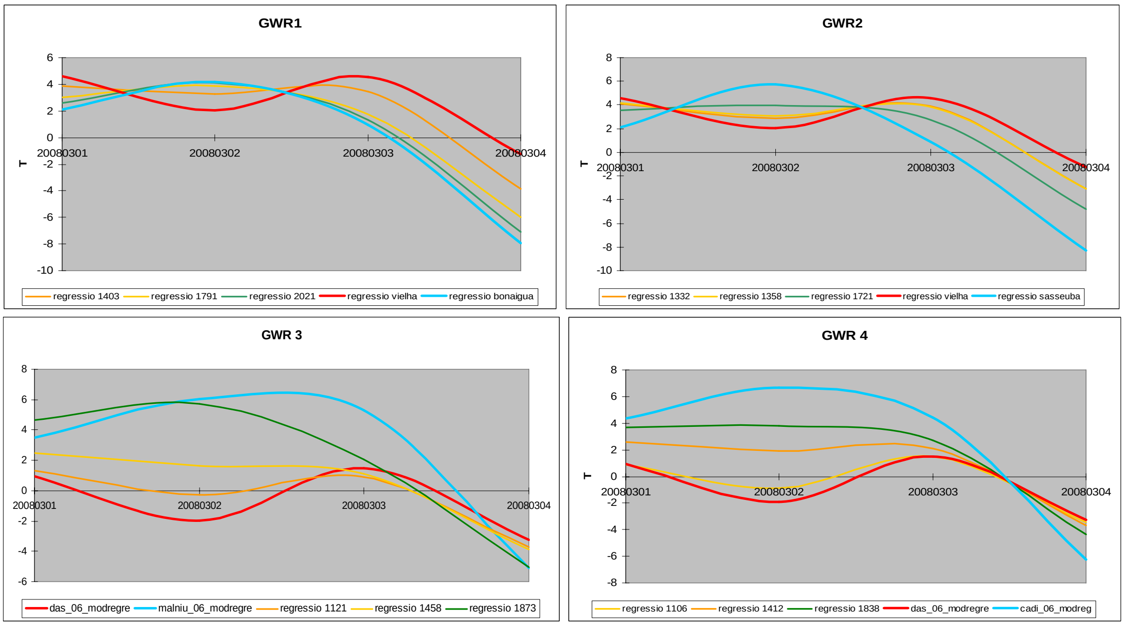

Figure 4.7. Temperatures obtained from GWR regressions across every transversal section in La Val d'Aran (GWR1 & GWR2) and La Cerdanya (GWR3 & GWR4).

5. CONCLUSIONS

Regressions are able to detect the real behaviour of temperatures in the analyzed valleys, although these ones better represent the mountain sites than the lower valley sites. But knowing that regressions are made using NWP data and knowing that NWP is not capable of detect ground level behaviours, it's possible to affirm that a multilinear regression fits to the objectives because it's able to detect boundary layer phenomena.
It's also remarkable that the results obtained with regression fit better than those obtained with the 4 km resolution model.

The main problem in this study is the lack of data in order to calculate the regressions and validate the GWR. Hence, to consolidate the good results achieved a longer temporal period is needed.

The differential behaviour of Das compared with all the other sites makes difficult to establish independent variables which explain the dependent variables. This suggests a future study concerning the different variables behaviour in La Cerdanya, especially temperature inversions.

The weight election in GWR cannot be made systematically and it is a limitation for operational use. In the future it is suggested to develop a new method to adjust these weights to some meteorological parameters calculated from meteorological variables.

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