Evaluation of ALARO-0 5km over Madeira

ALADIN-FR/LACE stay at the Institute for Meteorology (IM), Portugal

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1 Introduction

The main emphasis of the ALADIN-FR/LACE stay at the Institute for Meteorology (IM) in Lisbon/Portugal was to evaluate the performance of an ALARO-0 version running at 5km resolution on a domain centered over Madeira island in the North Atlantic. At the time of writing some work has already been invested within LACE and ALADIN to test ALARO-0 versions around 5km in a test/pre-operational environment (and an operational environment in Belgium).

The unique geographical environment of Madeira island provides a nice opportunity to test ALARO-0 in special conditions (isolated island, flow modifying topography, ...) and to evaluate whether running ALARO-0 on higher resolution (5km for the moment) can bring benefit with respect to versions running on coarser resolutions (9km). Beside a general verification computed for two 1-month periods several test cases where chosen to evaluate the impact of relevant model setups (vertical resolution, timestep).

Section 2 briefly describes the model setup and observation data used in the present study. Section 3 and 4 summarize the results for the case studies and the 'long time' verification. The final section 5 tries to point out the main conclusions.

Code version	CY35T1
Gridpoints	120 x 108
Horizontal res.	$5km$
Vertical levels	46
Orography	envelope
Coupling model	ARPEGE
Coupling update	3h
Dynamic kernel	hydrostatic
Physics	ALARO-0
Forecast range	30h
Timestep	180s
DFI	yes [1]
Init. hydrometeors	0

Table 1: Settings for 'reference' version (V04)

Version	Experiment ID	Characteristic
V04	212	see table 1
V01	210	same as V04 but $LSPRT = .FALSE.$
V02	211	same as V01 but timestep 60s
V03	213	same as V01 but 60 vertical levels [2]
V05	214	same as V01 but 90 vertical levels
–	203	ALARO 9km, setup equivalent to 210
–	001	ALADIN 9km, operational model at IM

Table 2: Experimental setup characteristics

2 Data

2.1 Model settings

The source code version for the present study is CY35T1 (export version), implemented on a IBM p5-575. The first task was to implement some minor source code modifications on top of the export version to be used during the tests. These changes adress cloud cover diagnostics as described in [1], diagnostics of screening level $T2M$ and $RH2M$ as described in [2] (finally not used in the tests) and the correction of a minor bug in 3MT.
Table 1 describes the ALARO-0 setup which was finally chosen to be run for the 'long time' verification periods. This version (named V04) can somehow be seen as a the 'reference' version. It should be mentioned that for version V04 namelist key $LSPRT$ (activating quantity RT to be spectral variable and to have the pressure gradient term computed more precise in case of precipitating species being present) is switched on. As it is not recommended (LACE personal communication) to activate this key during DFI, the model run procedure is split into a short forecast (e.g. 1 timestep) using DFI (with $LSPRT = .F.$) and the final forecast (without DFI and with $LSPRT = .T.$).

2.1.1 Experimental model setups

On top of the main or reference version (named V04) described in the previous section, several experimental setups were chosen to be used for the case studies. These experimental setups and their major characteristic are listed in table 2. The differences are adressing vertical resolution, timestep and finally also the $LSPRT$ key. The experiment ID numbers listed in table 2 will be used later on in this report for referencing the different model setups. As it can be seen there are three different vertical resolutions being used. They represent the actual (at the time of writing) operational resolution used at IM (46 levels), the operational one from ARPEGE (60 levels; differing from the 46 level distribution most notably in higher troposhere and stratosphere) and finally a new 90 level distribution, characterized through a significant increase of levels in the planetary boundary layer with respect to the 46 and 60 level distributions. Some more details can be found in the next section 2.1.2.
It should be mentioned that the decision to chose version V02 (using 60s timestep) as one of the experimental setups came up more or less 'by chance' as it turned out that model runs using the initially chosen timestep of 180s were aborting with floating point exceptions in several test cases (running on IBM p5-575). Some time was invested to understand the type of the problem, so the aborting runs were rerun using various MPI/OpenMP settings and different HPC platforms (IBM p6-575 at ECMWF, NEC SX-8 at ZAMG, NEC SX-9 at Meteo-France), whereas on vector machines the floating point exceptions did not occur. First it turned out that by reducing the timestep to e.g. 60s one can avoid the model blowing up. As this drastical decrease of the timestep might influence the model performance significantly there was interest to see the impact for the case studies, so it was finally chosen as one experimental setup (V02).

[1]LSPRT=.FALSE. during DFI, LSPRT=.TRUE. during integration
[2]vertical level distribution taken from ARPEGE

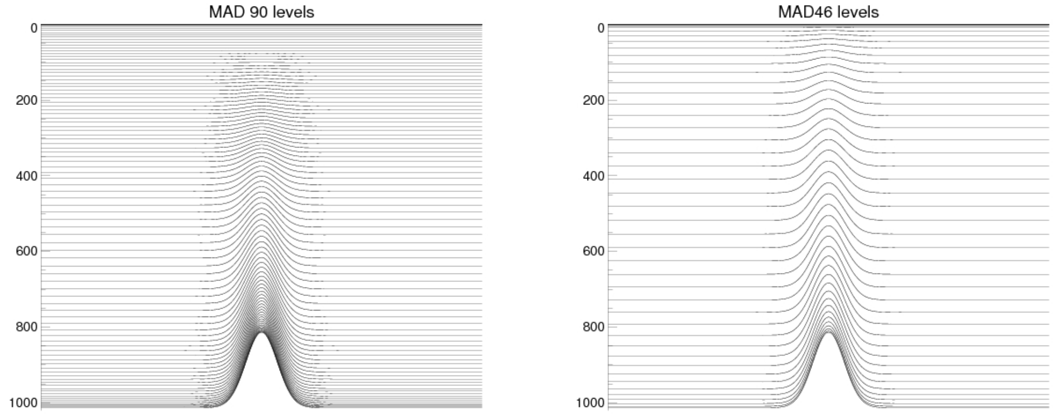

Figure 1: Left: 90 level distribution used for V05, right: 46 level distribution used for V01,V02,V04

It turned out that another possibility to prevent the model from aborting is to use just 1 processor, but the 'final clue' was to use parallelization just in in one direction (North-South) and not in both like it is done operational (without problems) for the ALADIN 9km version at IM. So finally the question why an aborting model is not observed on vector machines was answered, as parallelization is just used in one direction on vector machines.

2.1.2 Vertical resolution

As already mentioned three different types of vertical resolutions have been used for the case studies:

- 46: Vertical level distribution used at IM for the operational ALADIN model (see figure 1). Estimated number of levels in PBL (equivalent to number of levels below $850hPa$): 10.
- 60: Distribution used operationally for ARPEGE and ALADIN-FRANCE (at the time of writing). Estimated number of levels in PBL: 10.
- 90: New vertical distribution with a major increase of levels in the planetary boundary layer (PBL) (see figure 1). Number of levels in PBL: 22.

In order to create the 90 level distribution a program written by P. Benard and K. Yessad named 'AETB.F90' was used. This program computes the A and B coefficients defining the vertical distribution of model levels according to the user's wish (number of levels in PBL, number of levels in stratosphere, ...). A program documentation can be found from [3]).

2.2 Observational Data

On observations side the data sources for objective verification over Madeira island are surface station data and satellite pictures (IR and VIS) for subjective verifications (case studies). At the time of writing there are 8 stations (three of them SYNOP) located on Madeira main island and 1 on a smaller island named Porto Santo, which is located to the northeast of the main island. The station names, their geographical coordinates and their height can be read from table 3. As it can be seen there is one mountain station (named Areeiro) located in higher elevations (near the highest peak of Madeira island being Pico Ruivo with $1862m$ altitude) and another one in medium elevations (Lombo da Terca) located on the eastern slopes of the island. The other stations are located more or less at the coast, in elevations ranging from sea level up to $300m$. Figures 17 and 18 in appendix A help to get a better idea about the distribution of

ID	NAME	LAT	LON	HEIGHT
08521	FUNCHAL-S.CATARINA	32.68	-16.77	49
08522	FUNCHAL	32.63	-16.90	56
08524	PORTO-SANTO	33.07	-16.35	82
08960	SANTANA-SJORGE	32.83	-16.90	271
08973	AREEIRO	32.72	-16.92	1510
08986	PONTA-DO-SOL	32.67	-17.08	48
08990	CALHETA	32.82	-17.27	312
08978	CANICAL	32.75	-16.70	136
08980	LOMBO DA TERCA	32.83	-17.20	935

Table 3: Surface stations on Madeira

the surface stations on Madeira island (and Porto Santo) and the topographical characteristics of the island.

3 Case studies

3.1 Case selection

The climate on Madeira is primarily affected by the position of the 'Azores High', the semi-permanent centre of a subtropical high pressure area forming near Azores islands. Considering this information the following days/periods were chosen as case studies (many thanks to Maria Monteiro for doing this work!).

- **20090614 - 20090616**: During this period the weather sitution on Madeira is dominated by a cut-off low, resulting in general cloudy conditions over the island and significant precipitation amounts. Figure 19 in appendix A shows the ECMWF analysis for geopotential, temperature and wind in $500hPa$ for 20090615 12 UTC.
- **20090717 - 20090719**: This period was chosen as being representative for situations when Madeira is located on the east side of an anticyclon centered over Azores region, resulting in northeasterly surface winds for Madeira and surroundings (see figure 20 in appendix A).
- **20090918 - 20090921**: This represents again an anticyclonic situation, shortly disturbed by a weak upper air low. The period is characterized by easterly to northeasterly surface winds (see figure 21 in appendix A) and low cloudiness mainly caused due the flow being lifted along the islands mountain ridges.
- **20080811**: This day was chosen as a case where the so called 'von Karman vortex street clouds' can be observed (at least to a certain extent). It is again a case with a high pressure system centered over Azores region dominating the synoptic scale motions, Madeira facing northerly winds on the east side of the anticyclon.

3.2 Results

The conclusions drawn from the test cases might not be valid in general (this has to be explored running long term tests, see section 4), but at least they help to raise some questions/problems or provide some good reason to test a certain setup for an extended period.
In order not to overload the present report with figures, just a few representative plots are presented in the following. The paramters of main interest are 2m temperature, 2m relative humidity, 10m wind speed and direction, precipitation and total cloudiness. As already mentioned the experiment ID numbers used in the plots can be read from table 2.

3.3 2m temperature

- High resolution versions (ID numbers 210-214) tend to overestimate the diurnal cycle of temperature in the near surface layers in a significant number of cases. This overestimation can be observed at all stations. One may argue that this overestimation can be easily explained for stations located at the coast in cases when the wind forecast is wrong (wind coming from the sea resulting in a damped diurnal cycle while model is producing a different scenario...). Figure 2 shows that type of case (Ponta do Sol). But as the overestimation can also be observed in a number of cases when the forecast for wind direction is correct (see figure 3) the problem is a more complex one. Due to this overestimation the benefit of the 5km version with respect to the 9km version cannot be shown for the case studies, except for Porto Santo (see next item).

- Increasing the number of vertical levels has a significant impact on the near surface temperature forecast. This impact is positive in a number of the cases, as the generally overestimated diurnal cycle is significantly damped and therefore closer to reality. Figure 3 shows this type of case (for station Porto Santo): The 5km versions generally overestimate the amplitude of the diurnal cycle, whereas the version running with 90 levels (214) gives a significantly better result. It would be interesting to have a vertical profile for this case, in order to see whether the 90 level version is better for the right reason (better vertical structure,...).
  Figure 3 also shows that the ALARO-9km version (203) is not able to simulate the conditions for this small island, so for Porto Santo the 5km versions are better.

- Decreasing the timestep to 60 seconds also has a significant impact on the forecast results, whereas a tendency towards a further amplification of the diurnal cycle can be observed in case of 2m temperature. This further exageration often leads to a worse representation of the observed amplitude.

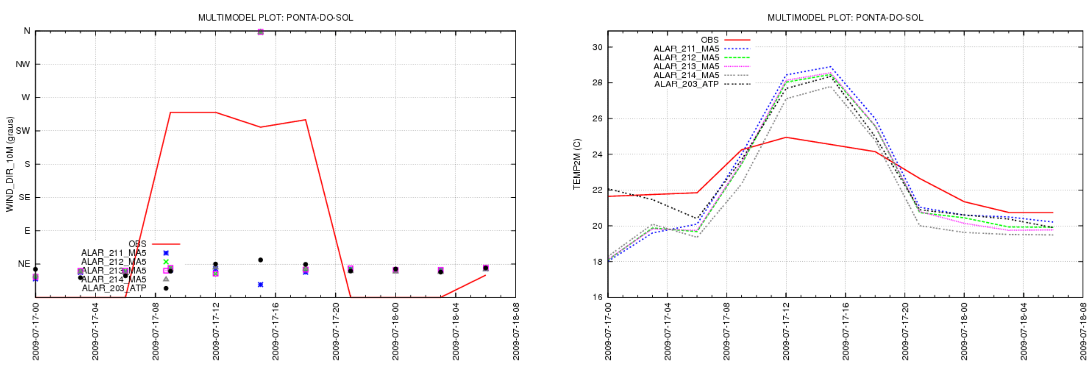

Figure 2: Left: 20090717 00 UTC 10m wind direction forecast for various 5km versions, right: 20090917 00 UTC 2m temperature forecast

3.4 2m relative humidity

- For near surface relative humidity forecasts the benefit of running a 5km version is significant in a number of cases, giving a better representation of the near surface humidity evolution.

- Although an impovement of near surface humidity forecast can be observed, the quality of the forecasts keeps space for improvement.

- The increase of vertical resolution changes the model results in most of the cases. It can not be clearly pointed out from the selected cased out whether this impact is positive or

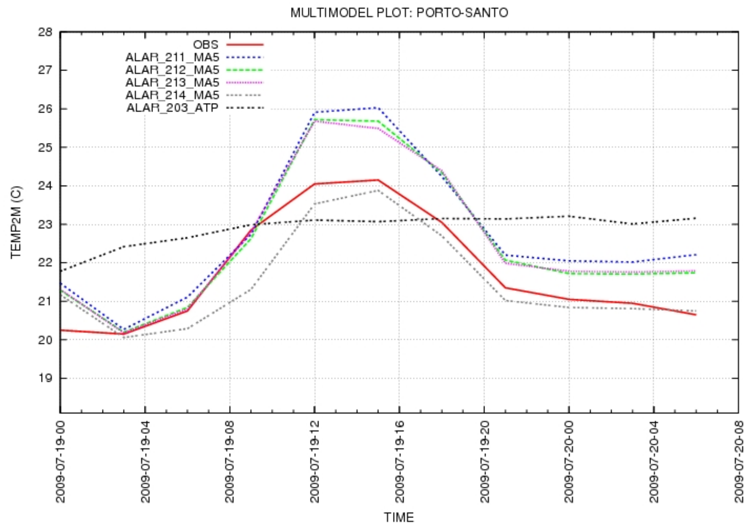

Figure 3: T2M forecast for various 5km versions (211,212,213,214) and 9km model versions (203) for 20090719 00 UTC for Porto Santo

negative. There is a positive impact on e.g. Funchal results, a negative one for S.Catarina. The 'long time' verification can give a better view (see section 4.2).

- Using a shorter timestep has significantly less impact on the near surface humidity forecast than on the 2m temperature forecast.

3.5 10m wind

- The impact of higher resolution is weaker than for near surface temperature and relative humidity.
- The type (positive/negative) of this impact is differing from station to station. There are stations with significant better results for wind speed (e.g. Calheta, Funchal), but also some with worse results (Areeiro). Figure 4 shows representative cases for Arreiro and Funchal.
- An increase of vertical resolution has smaller influence on results with respect to the impact observed for surface temperature or humidity.
- For wind direction the differences among 5km and 9km and higher/lower vertical resolution gets smaller, the weaker the wind gets.

3.6 Precipitation

- For precipitation, it is hardly possible to draw conclusions concerning the comparision of 5km and 9km versions.
- The same is valid for the comparison of lower/higher vertical resolutions. The impact of vertical resolution on the precipitation forecast is noticable, but it is not possible to draw conclusions out of the case studies.
- The version using 'LSPRT=.TRUE.' (212) differs significantly from the others running with 'LSPRT=.FALSE.' in cases with higher precipitation amounts (see figure 5). The impact for other parameters (t2m, rh2m, ...) is also visible (up to a certain extent) in these cases.

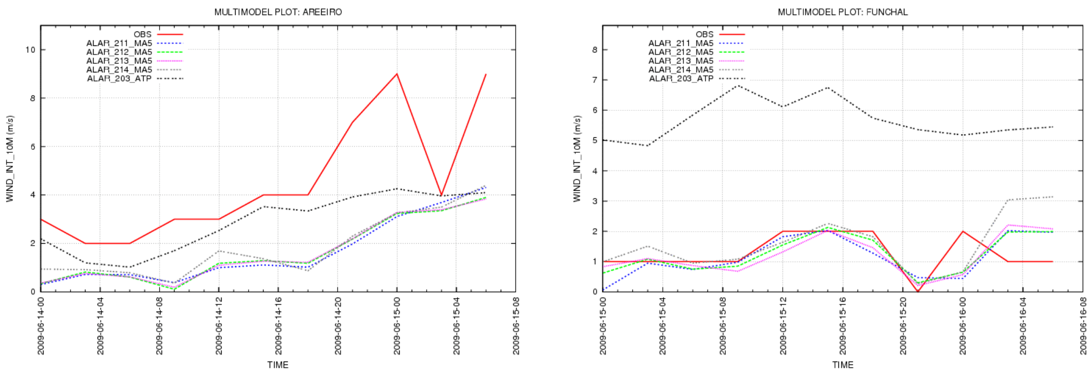

Figure 4: 10m wind speed forecast coming from various ALARO-5km setups (211-214) and ALARO-9km (203). Left: station Areeiro (20090614 00 UTC), right: station Funchal (20090615 00 UTC)

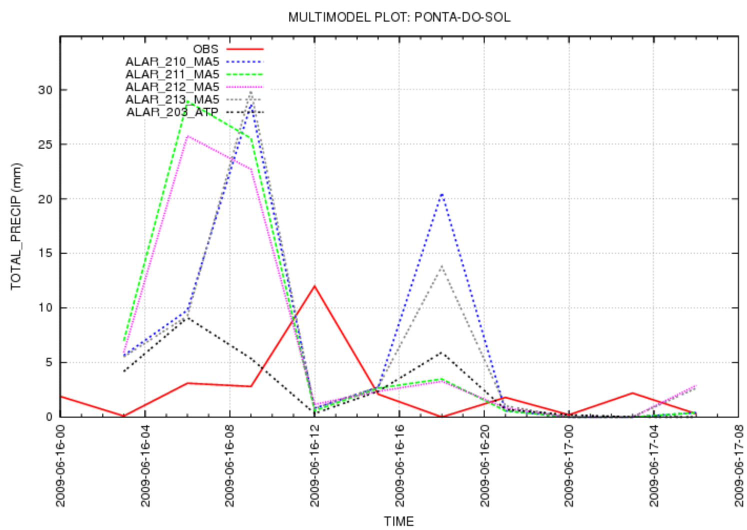

Figure 5: Total precipitation forecast for various 5km versions (210,211,212 and 213); version with LSPRT (212, magenta) shows significant differences with respect to other versions

3.7 Total cloud cover

- To quantify the quality of cloudiness forecasts the SYNOP data is not sufficient (and one may question whether it is usefull to compare total cloud cover observations with model values, see section 4.5). So just a subjective evalutation for the case studies could be made through a visual comparison with satellite images (MSG VIS and IR).

- The various ALARO-5km versions are using $LACPANMX$ key (near maximum overlap version for cloud diagnostics, see [1]) activated , whereas the weight for the "maximum overlap of adjacent cloud" version ($WMXOV$) is set to 0.8. This value represent the tuning found appropriate for the actual vertical resolution used in ALADIN-AUSTRIA (60 levels, aequivalent to the one used for version with experiment ID 213 during these experiments). Figure 6 shows the total cloud cover forecast for station Calheta. It can be seen that there is the tendency that versions using an increased vertical resolution tend to produce more total cloudiness (214 > 213 > others). As $WMXOV$ has been tuned for 60 levels, a retuning (probably lower value) should be considered for higher vertical resolutions.

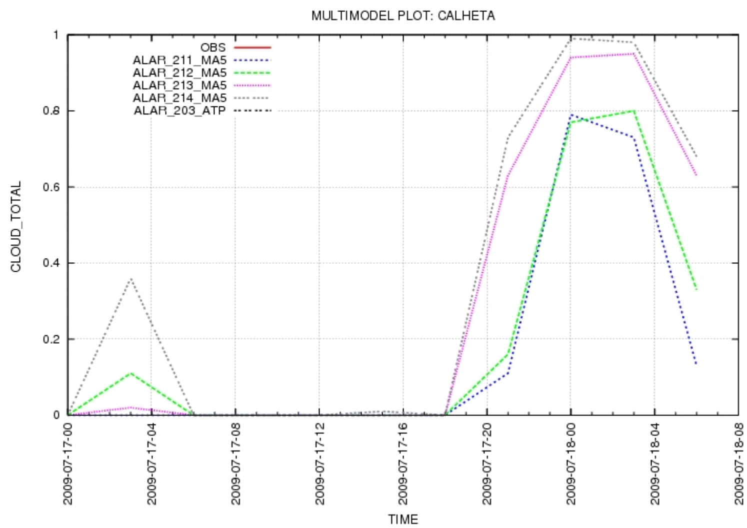

Figure 6: Total cloud cover forecast for various 5km versions (211,212,213 and 214); no observation available

3.8 'Von Karman' Case

Figure 7: MSG infrared pictures for 20080811 1130 UTC (right) and 0900 UTC (left) showing the buildup of vortex-typed cloud formations downstream Madeira(Karman vortex street)

This case (20080811) represents the situation when a so-called 'von Karman vortex street' is forming. This phenomenon can be observed when eddies, built on the leeside of an obstacle located in a streaming fluid (e.g. island of Madeira), detach from the obstacle more or less regularly and are advected with the flow further downstream. More information (and nice pictures) can be found under e.g. [4].

As this phenomenon occurs rather seldom, it was not an easy task to find a case in the recent past (thanks to Margarida!!). Finally 20080811 turned out to be one, not perfect, but a nice opportunity to test whether any similar feature is produced in the model. As this case was found rather late (during the stay) and as the coupling files had to be reproduced from ARPEGE at MF the time to study this case was very short.

Figures 8 and 9 show the wind foreacast for two different forecast lead times ($+09h$, $+12h$). One can see that there is a vortex forming downstream Madeira island. In figure 9 a second vortex can be seen further downstream, rotating in opposite direction compared to the first one. So the wind field (in 925 hPa) seems to be somehow appropriate for building vortex cloud streets, but for this day the model is completely missing the (widespread) low cloudiness occurring in reality (seen from satellite pictures).

It would be advisable to have a further look on other model fields, like (absolute) humidity quantities in lower levels. One may expect to see these vortices as rather dry 'objects' within a more humid surrounding, even when there is no signal in the diagnosed cloudiness coming from the model. This is what can be seen on the satellite picture (see figure 7). The vortices are more or less inhaling drier air from the island procuding a cloud free area within the vortex. Unfortunately the time was to short to do further investigations and to visualize various humidity for some lower levels in an appropriate manner.

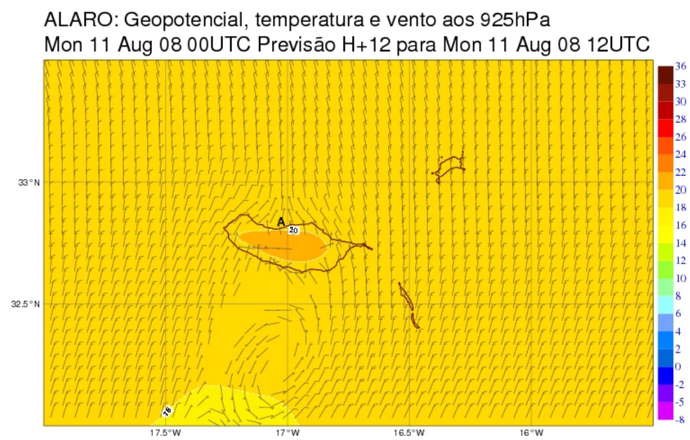

Figure 8: ALARO 925hPa wind and temperature, 20080811 00 UTC + 12h

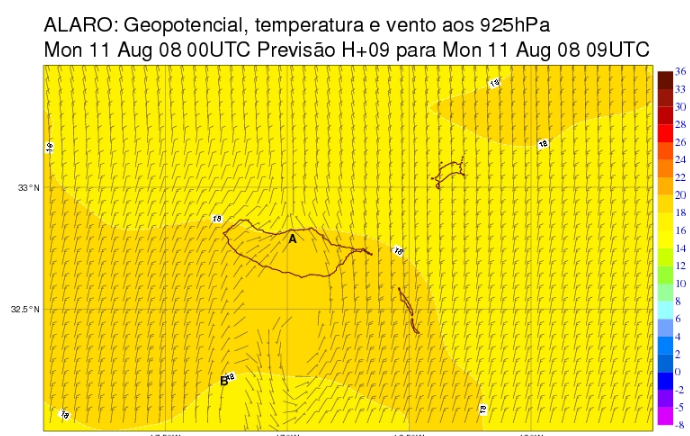

Figure 9: ALARO 925hPa wind and temperature, 20080811 00 UTC + 09h

4 Long term verification

In addition to the case studies ALARO-5km was run for two 1-month periods (just 00 UTC runs):

- **20090201-20090228** This month was chosen as it represents a period when Madeira and the surrounding areas were affected by a number of atmospheric disturbances crossing the Atlantic, causing some major precipitation cases.
- **20090601-20090630** This period is charaterized by generally stable conditions for Madeira, which means that the island is facing mainly easterly to northeasterly surface winds ((according to the position of the Azores high).

It is important to mention that it is ALARO 5km version v04 (experiment ID 212 in table 2) which was run for the two 1-month periods (and finally compared with the operational ALADIN model running at IM). In the figures shown below the ALARO 5km version is labeled as 210 (for some technical reasons). The performed verification was mainly concentrating on point forecasts for 2m temperature, 2m relative humidity, 10m wind speed and direction, precipitation and total cloudiness. To create (and plot) the scores a nice software package which is being developed at IM has been used. In the following the most important results are presented.

4.1 2m temperature

During the verification it turned out that 2m temperature coming from ALARO 5km is the parameter showing the worst performance with respect to the operational ALADIN model at IM (similar conclusions have alredy been drawn from the case studies). Figure 10 shows the percentage of correct 2m temperature forecasts (allowing deviations of +/- 1 degree) for the period 20090201-20090228, whereas all available stations on Madeira (including Porto Santo) are taken into account. It can be seen that the curve for operational ALADIN model (labeled

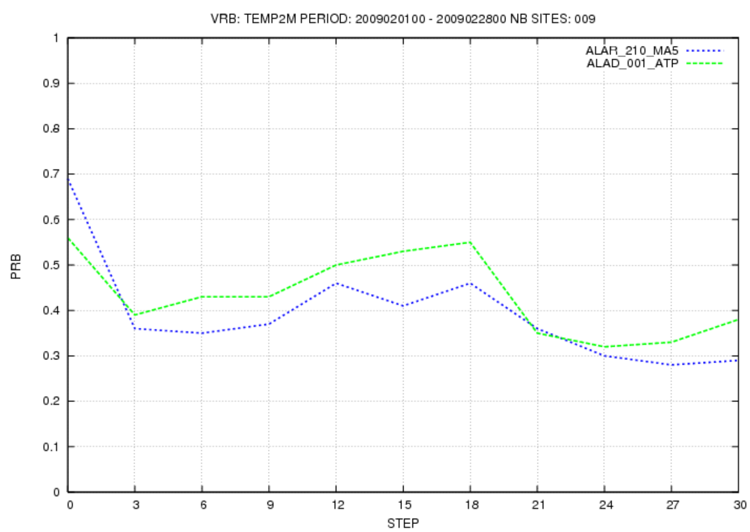

Figure 10: Percentage of correct 2m temperature forecasts (allowing deviation +/- 1 degree)

001) shows better percentage than the one for ALARO 5km (labeled 210). Figure 11 shows the bias curves for February 2009. The diurnal cycle in terms of bias is much more evident for the ALARO 5km version. So the model tends to be too cold during night (and in the morning), during daytime there is no bias (in average for all 9 stations). In order to give more details about the distribution of the bias with respect to the different stations in Madeira, figure 23 in appendix A shows the bias for Februar 2009 for lead time +6, which is (according to figure 11) a lead time showing a big cold bias. It is evident that all stations show this negative bias, but station 'Ponto-do-Sol' is the one with a significant colder bias compared to the others. It would be interesting to go more into detail, considering the exact location of the station to see whether it is a representative one.

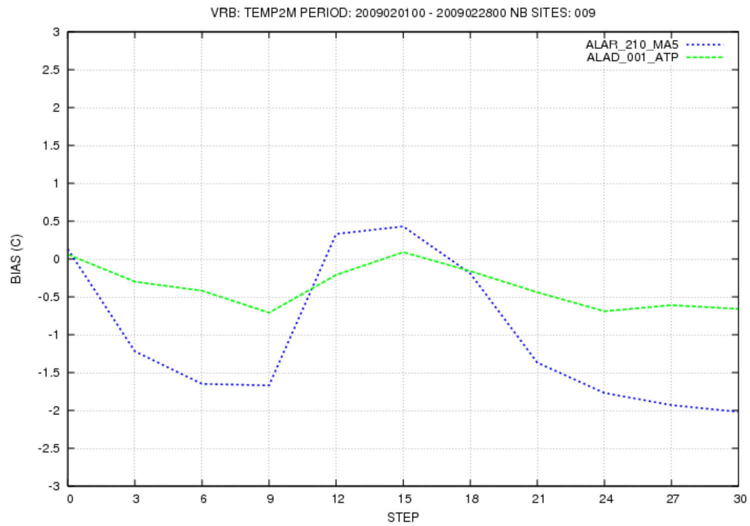

Figure 11: Bias for 2m temperature forecasts

The situation for June is the similar (no figures shown here), but one aspect should be mentioned: The bias is even bigger/colder for ALARO 5km (and also for ALADIN 9km). As a great part of the general forecast error for 2m temperature is due to the large cold bias (ocurring during night), it would be interesting to test whether the modified diagnostic of screening levels (described in [2]) can improve the situation. Unfortunately there was not enough time to test this.

4.2 2m relative humidity

The situation for 2m relative humidity is different. Figures 12 and 13 show the percentage of correct 2m relative humidity forecasts (allowed deviation: +/- 10 percent). It can be seen that the percentage for ALARO-5km is higher than the 9km ALADIN version for most of the lead times, especially for February 2009. For June 2009 the ALARO 5km curve temporarily falls below the ALADIN 9km one in the afternoon. Taking a look on the scores for the various stations (see figure 24 in appendix A) it can be seen that there are two stations showing a remarkable high bias for February 2009: Areeiro and Ponta do Sol. For June 2009 the situation is similar for Areeiro, showing a large dry bias. The bias for Ponto do Sol for June is significantly smaller, therefore station Calheta shows a dry bias with a magnitude comparable to the one for Areeiro.
So in general the quality of the relative humidity forecasts shows big errors (it might be advisable to verify also some absolute humidity quantity) but the benefit of using ALARO 5km is visible for relative humidity.

4.3 10m wind

For 10m wind speed the positive impact of running a 5km model is rather clear. Figures 14 and 15 show the percentage of correct 10m wind speed forecasts (including tolerance of 1m/s). In both graphs the 5km versions show a significant higher percentage of correct forecasts than the operational 9km version of ALADIN. Considering the bias values for the different station, it is obvious that station Areeiro shows a significant negative bias. The forecasts for the other stations, located in lower altitudes, show tendencies to overestimate wind speed in the afternoons (see figure 26 in appendix A). For wind direction the situation is less clear, but the scores are still neutral to slightly positive for the 5km version (not shown).

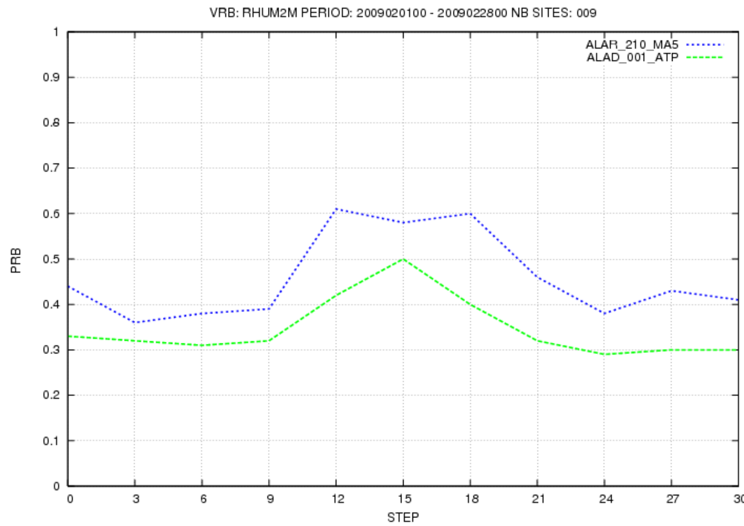

Figure 12: Percentage of correct 2m relative humidity forecasts (allowing deviation +/- 10 percent)

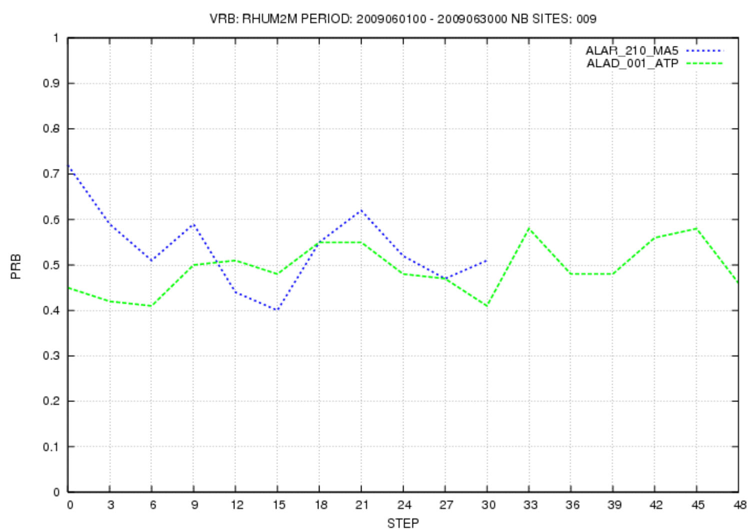

Figure 13: Percentage of correct 2m relative humidity forecasts (tolerance +/- 10)

4.4 Total precipitation

Comparing the precipitation forecasts for station points coming from two models with different horizontal resolution (ALARO-5km and ALADIN 9km) is not an easy task (and probably not a fair one for ALARO 5km). It would be advisable to use a more sophisticated method for precipitation verification in order to avoid some double penalty syndrom for the high resolution model. At IM in Lisbon some effort has already been invested to implement more sophisticated verification methods (fuzzy method), using not only the nearest model gridpoint (with respect to the station location), but also surrounding gridpoints (which may better represent the observed value). In order to consider area mean precipitation and also structure or location of the precipitation forecasts some gridded precipitation analysis (radar, rain gauge,..) would be necessary.
For the present verification, the skill scores for ALARO-5km and ALADIN-9km were calculated using the rain gauge measurements available on Madeira and the nearest model gridpoint. Using

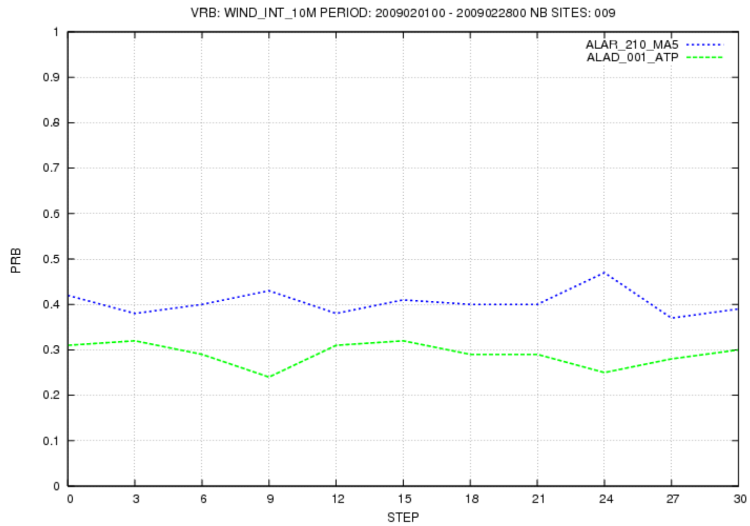

Figure 14: Percentage of correct 10m wind speed forecasts (allowing deviation +/- 1 m/s)

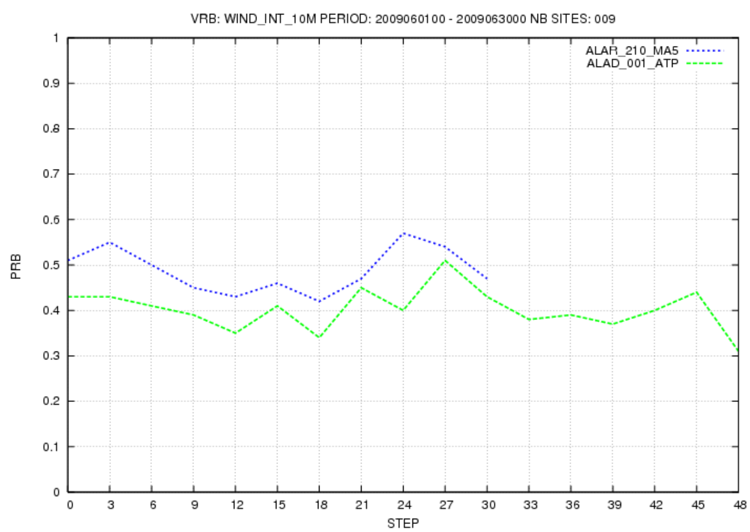

Figure 15: Percentage of correct 10m wind speed forecasts (allowing deviation +/- 1 m/s)

Equitable Threat Score (ETS) and Heidke Skill Score (HSS) there is no clear signal (one may expect this) whether ALARO-5km brings better results than the 9km version. Figure 16 shows ETS for February 2009 (for 24h accumulated precipitation intervals). From this plot one can read that the skill is rather low for medium intensity precipitation events and that ALARO-5km has (a little) more skill for low and high intensity events. The plot for June looks similar (not shown).

4.5 Cloud cover

Verification of total cloud cover using station observations is even more problematic in the present study. One reason for that is that there are too few observations for cloud cover on Madeira. The second reason is that it may be questionable to compare model values for total cloud cover, valid for a gridbox with a given dimension (9km and 5km in this case), with total cloud cover observations, being valid for the observers visual range (in general bigger than a 5km or 9km gridbox). The higher the model's resolution, the more binary the character of

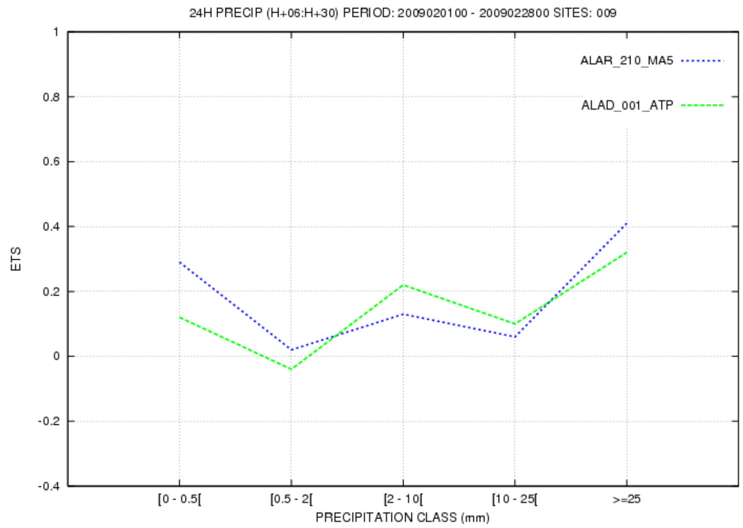

Figure 16: ETS for 24h precipitation forecasts (period 20090201 - 20090228)

total cloud cover gets. In order to make these values comparable with obervations one should build mean values over the surrounding gridboxes. In the present verification this is not done, so observations are just compared with the model value at the nearest gridpoint. The results show that it is not really possible to make any conclusions on quality of cloud cover.
A better way is to use satellite data for comparison with the model data. But for that the implementation of more sophisticated software would be necessary (computing synthetic satellite images out of model data etc.).

5 Summary

During this stay several ALARO-5km versions (differing in terms of vertical resolution, timestep, ..) were run for selected test cases on a domain centered over Madeira and finally one version was chosen to be run for two 1-month periods in order to be compared with the operational ALADIN 9km version used at IM to see a possible benefit of using a 5km version over Madeiera. Based on the case studies and the two long period runs some conclusions can be drawn, the most important can be pointed out as:

- The benefit of running a ALARO 5km version is visible for most of the considered parameters (in particular for 2m relative humidity, wind speed and direction), but there is one exception:
- 2m temperature turned out to be the quantity producing worse results compared to the operational 9km ALADIN versions (and the 9km ALARO version during test cases).A part of the 2m temperature problem (cold bias during night) might be removed by using the modified screening level diagnostics (see [2]).
- Increasing the vertical resolution seems to be a potential candidate to improve the near surface forecasts in a number of cases and may solve another part of the 2m temperature problem. The results show that it is worth to continue working with higher resolution to see whether this (often positive) impact can also be seen in other geographical environments.
- Increasing the timestep while keeping the same resolution has a significant impact on the model results. It may be interesting to understand more how this impact is acting (and finally resulting in e.g. a further amplification of the diurnal 2m temperature cycle).

- The 'von Karman' case shows that the model is able to create at least some features in the wind field which may result in the formation of von Karman vortex cloud streets. It may be interesting to invest more time on this case.
- In order to evaluate objectively the benefit of precipitation forecasts coming from a 5km model (with respect to a 9km model), gridded analysis and objective based verification methods are advisable. In case of precipitation there has already been some work invested within ALADIN/LACE to implement and use new methods (e.g. SAL). For total cloudiness the methods used for precipitation may also be used after some adaptions (using satellite data).

Acknowledgement Finally i would like to thank the whole Portuguese NWP team for their warm welcome and great hospitality. In particular i would like to thank Maria Monteiro, Joao Rio, Nuno Lopes and Manuel Joao Lopes for their help in technical and scientifical questions during my stay at IM.

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[1] C. Wittmann (2008): Near Maximum Overlap Version for ACNPART. LACE report, available from *www.rclace.eu/?page=12* .

[2] L. Kullmann (2008): New interpolation formula in stable situations for the calculation of diagnostic fields at measurement height. Presentation given at 19th ALADIN workshop / HIRLAM ASM 2009, available from *www.cnrm.meteo.fr/aladin/IMG/pdf/ME_LKu.pdf*

[3] P.Benard (2004): Design of the hybrid vertical coordinate η. Available from *www.cnrm.meteo.fr/gmapdoc/spip.php?article62&artsuite=1*

[4] *http://www.weathervortex.com/*

A Appendix

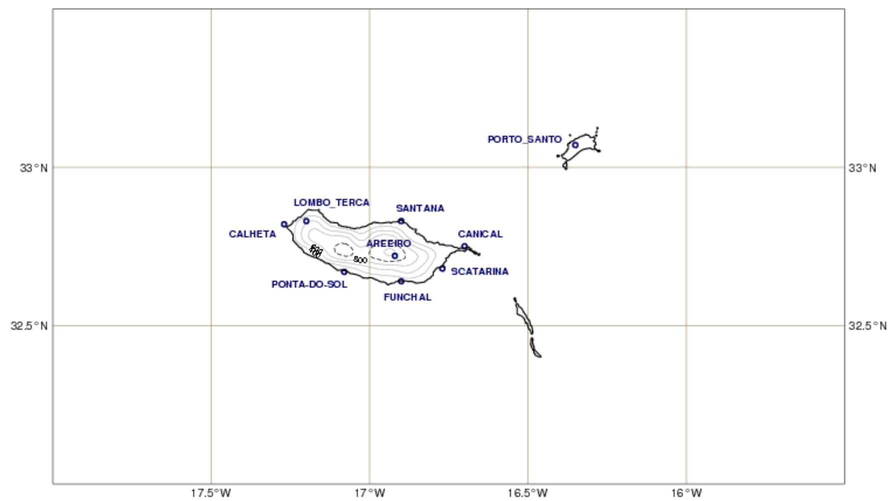

Figure 17: Location of surface stations on Madeira main island and Porto Santo

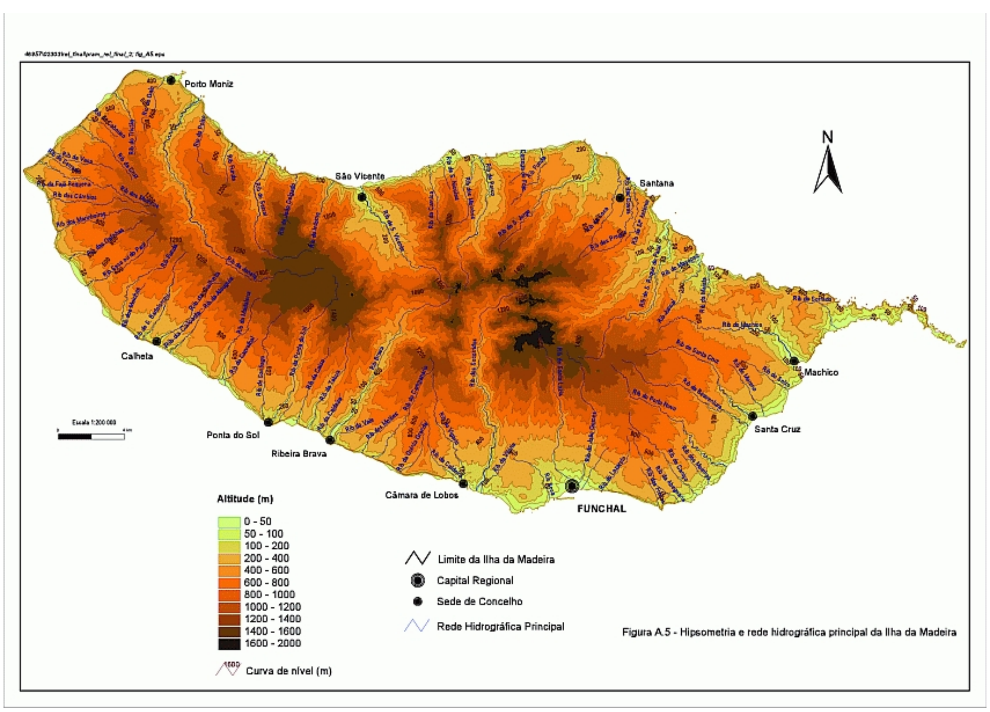

Figure 18: Topography of Madeira main island, taken from *http://madeira-gentes-lugares.blogspot.com*

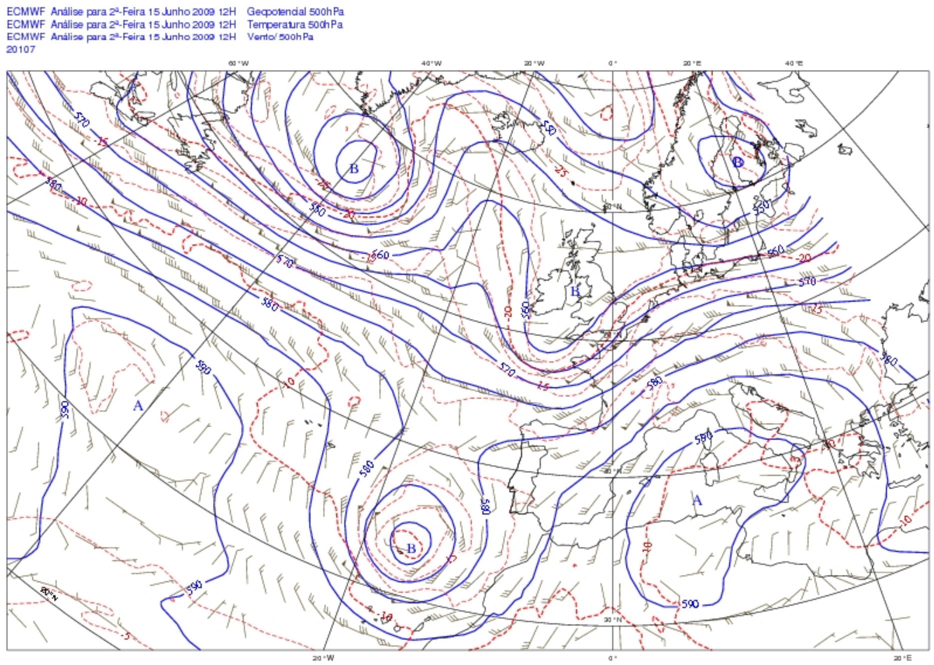

Figure 19: ECMWF analysis (500hPa geopotential, temperature and wind) showing a cut-off low as the dominating weather system for Madeira; analysis time 20090615 12 UTC

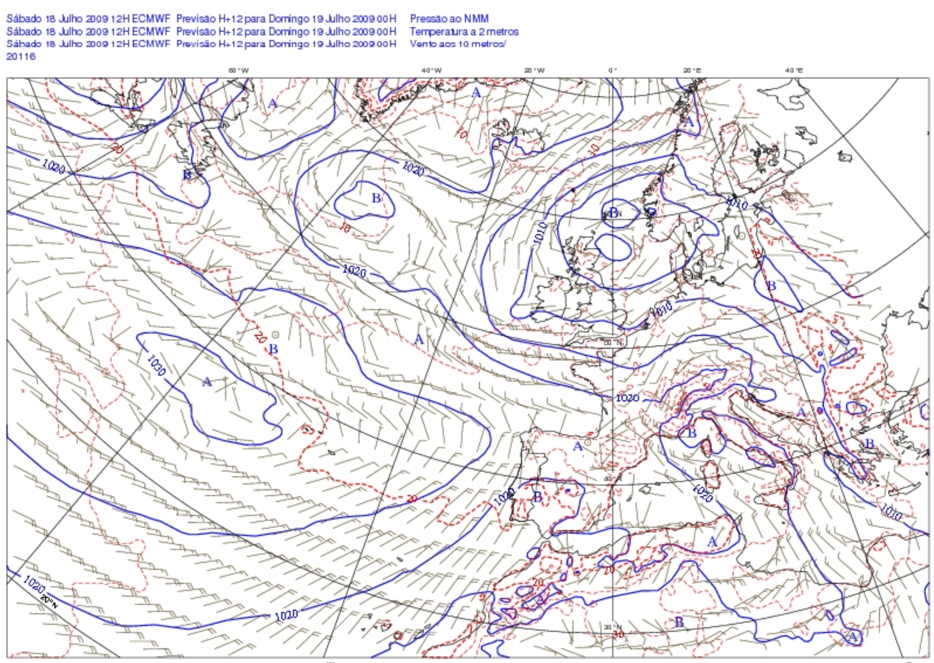

Figure 20: ECMWF 20090718 12 UTC + 12h foreacst for 10m wind, mean sea level pressure and 2m temperature.

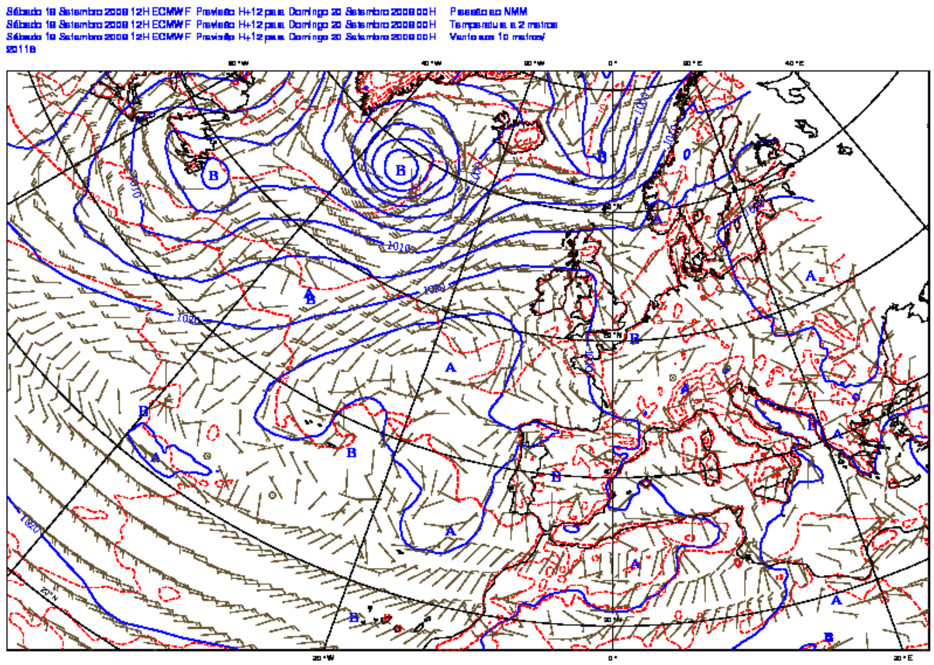

Figure 21: ECMWF 20090719 12 UTC + 12h forecast for 10m wind, mean sea level pressure and 2m temperature.

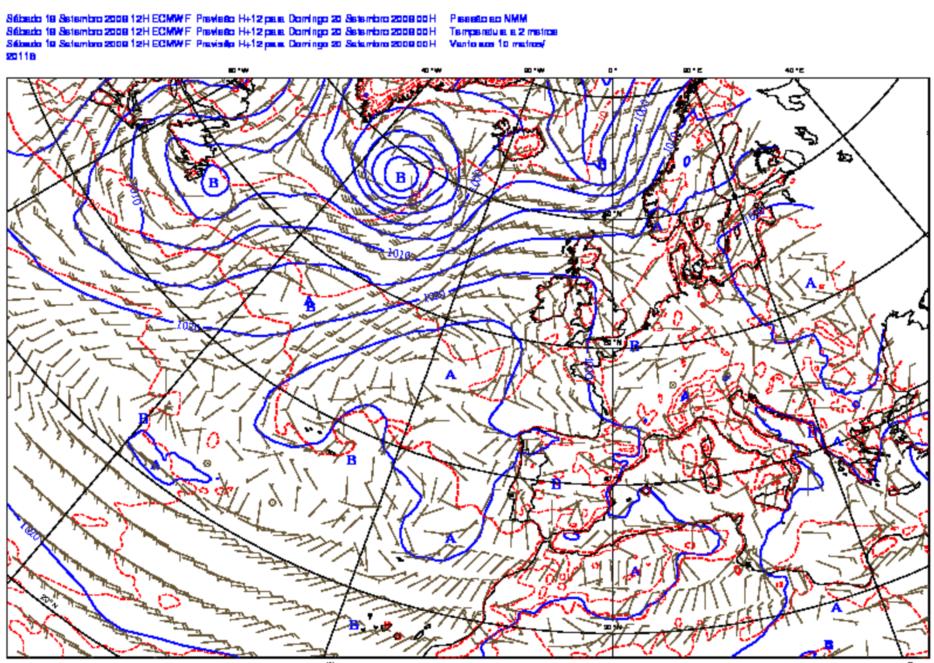

Figure 22: ECMWF 20090919 12 UTCs + 12h forecast for 10m wind, mean sea level pressure and 2m temperature.

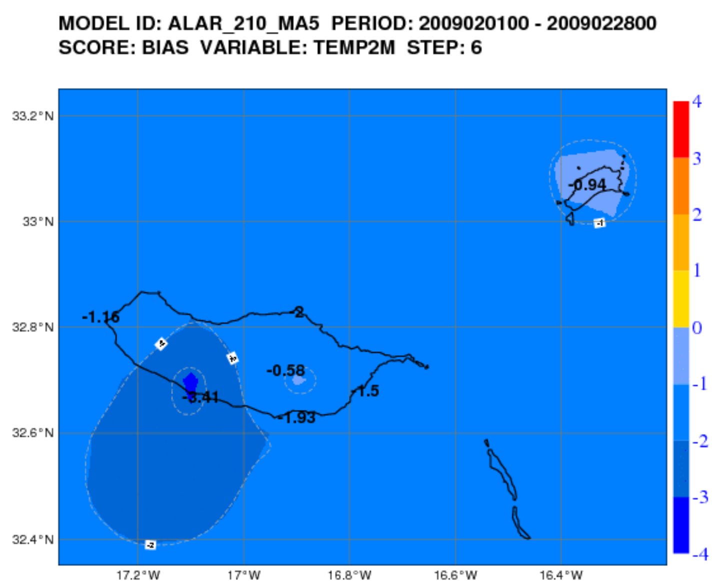

Figure 23: Map showing bias values (T2M) for different stations on Madeira for ALARO 5km (February 2009)

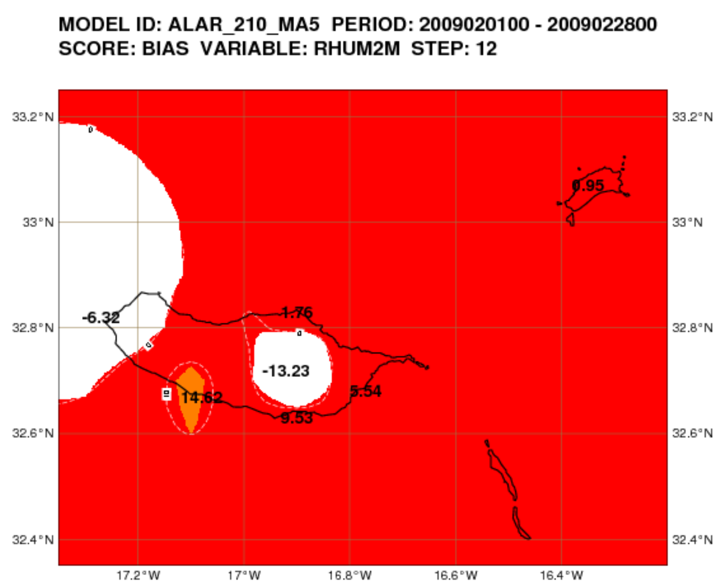

Figure 24: Map showing bias values (RH2M) for different stations on Madeira for ALARO 5km (period February 2009)

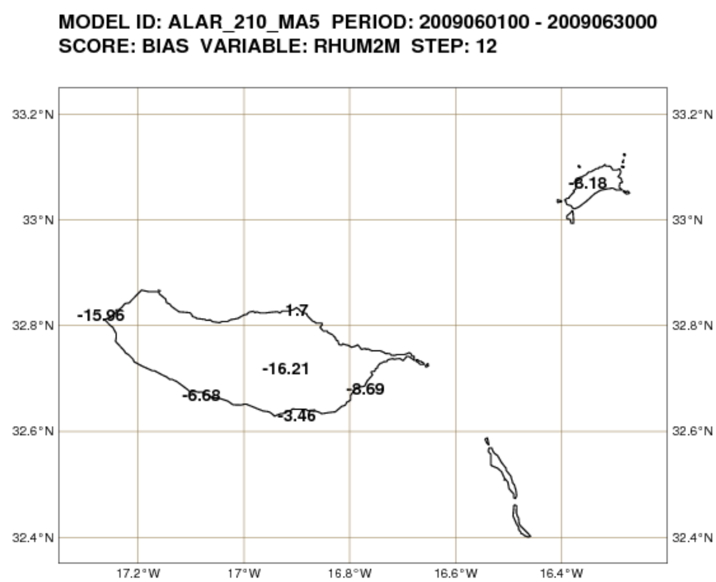

Figure 25: Map showing bias values (RH2M) for different stations on Madeira for ALARO 5km (period June 2009)

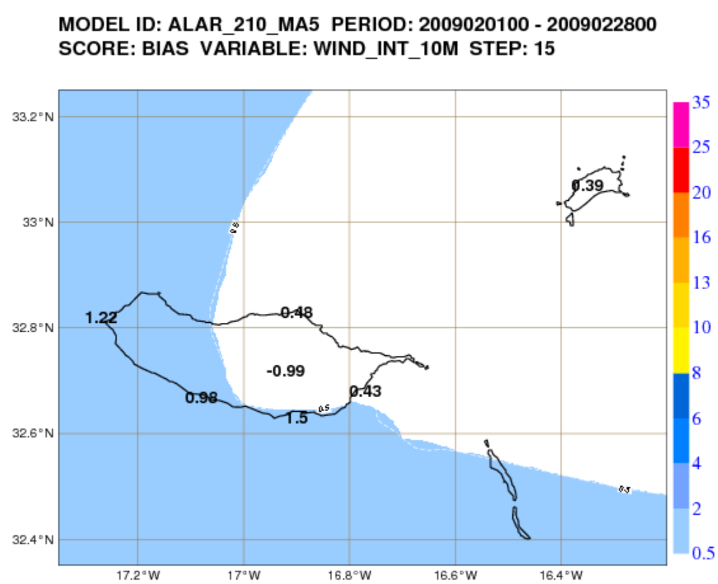

Figure 26: Map showing bias values (10m wind speed) for different stations on Madeira for ALARO 5km (period June 2009)