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On the vertical profiles of temperature, relative humidity and wind in the nighttime period in central mainland Portugal

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Abstract

In the framework of the FireStorm project, four portable weather stations were installed in the Lousã/Estrela mountain range. The data observed with this equipment, along with two other stations from the Portuguese Institute for Sea and Atmosphere's network of surface weather stations, allows the monitoring of the vertical profile of temperature, relative humidity and wind in the region. Many forest fires in mainland Portugal affect areas with complex terrain, with hills or mountains in the 400-1200 m asl range, where weather conditions strongly influence the fire propagation and lifetime. Therefore, it becomes even more pertinent to study the vertical profiles of temperature, humidity and wind as they often exhibit large variability, namely in the nighttime period. This paper provides an overall assessment of the weather conditions in the nighttime period in selected events in which significant temperature inversions or downslope windstorms were observed. The forecast skill of the two operational numerical weather prediction models used at IPMA is also provided and highlights the challenges of weather forecasting in areas with complex terrain.

1. Introduction

Most of the major forest fires in mainland Portugal occur in the summer period and are located north of river Tagus, in areas with complex terrain, typically with hills or mountains in the range 400-1200 m asl. Often it is considered that in the nighttime period lighter winds, lower temperatures and the recovery of the relative humidity contributes to lower rates of fire spread and reduced fire intensity (Potter, 2012). Although this behaviour is commonly observed close to the surface over plains or plateaus, it is not necessarily the case in complex terrain. Additionally, the effects of complex terrain on the flow must be addressed, particularly in the case of dynamically driven winds, as these tend to be stronger (Sharples, 2009; Werth *et al.*, 2011). Well known effects include flow over mountains with speeding/blocked flow, gap or corner winds, mountain wakes and channelling effects.

Recent work suggests that fire intensity in the nighttime has increased globally, which is linked to warmer and drier nights (Balch, 2022). This suggests that it is highly recommended to carefully monitor the variability of the weather conditions during nighttime, particularly in areas that are prone to large wildfires and where extreme fire behaviour is likely to play a relevant role. In the framework of the FireStorm project, four portable weather stations were installed in the north-western slope of the Lousã/Estrela mountain range. This region has benefits such as the easy access, it is in the middle of the area where most of the forest fires occur and it spans a wide range in altitudes. Additionally, the network of surface weather stations of the Portuguese Institute for Sea and Atmosphere (IPMA) has data at two other locations in the area, which ultimately allows a higher spatial resolution.

In Rio *et al.* (2022) an overview of the weather conditions in the summer 2021 and in the winter 2021/22 was given, with insight into the differences that are observed in the daily cycle of the stations within the slope. An evaluation of the observed weather conditions allowed the identification of significant weather events, such as frequent surface inversions in the valley stations, sharp inversions aloft due to warm air advection or large-scale subsidence and downslope windstorms.

This paper presents further results from the observed data in the Lousã/Seia region. In this paper the overall forecast skill of numerical weather forecasts (NWP) is provided. The forecasts used in this study are from the two operational NWP models used at IPMA. This paper also presents three events, in which significant temperature inversions or downslope windstorms were detected in the area.

2. Location and data availability

Figure 1 shows the area being monitored in this study, with a total of six weather stations. Two of them are from the surface network from IPMA and the other four are the new portable weather stations installed in the Lousã and Seia regions. The location of the new portable weather stations was chosen considering the availability of two other stations from IPMA and the need to monitor the slope in a range of altitudes as wide as possible. Tables 1 and 2 provide details about the weather stations used, respectively, in the Seia and Lousã regions.

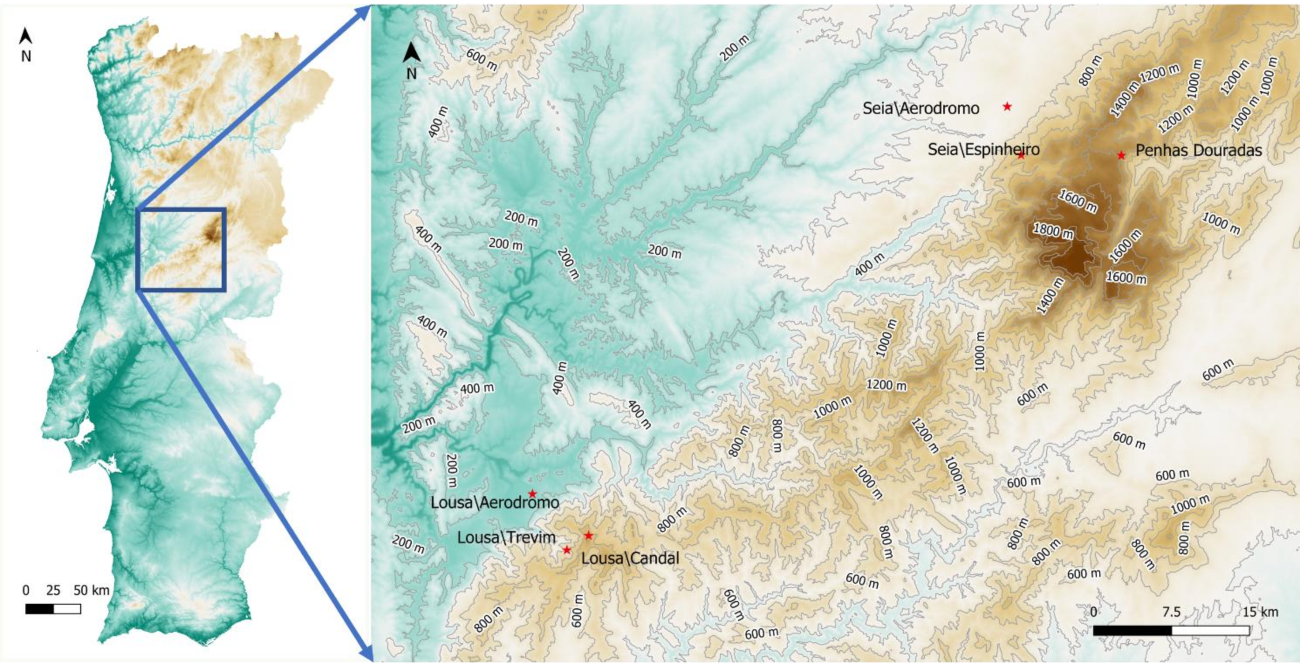

Figure 1 – Location of the weather stations used in this study.

Table 1 – Identification of the weather station in the Seia region.

Station name (short name)	Latitude	Longitude	Altitude [m]	Source	Available since
Penhas Douradas	40.41°N	7.56°W	1380	IPMA	---
Seia-Espinheiro (Espinheiro)	40.41°N	7.67°W	995	IPMA/FireStorm	03.2020
Seia-Aeródromo (Seia-Aero)	40.46°N	7.69°W	438	IPMA/FireStorm	03.2020

Table 2 – Identification of the weather station in the Lousã region.

Station name (short name)	Latitude	Longitude	Altitude [m]	Source	Available since
Lousã-Trevim (Trevim)	40.09°N	8.18°W	1167	IPMA/FireStorm	02.2021
Lousã-Candal (Candal)	40.08°N	8.20°W	621	IPMA/FireStorm	02.2021
Lousã-Aeródromo (Lousã-Aero)	40.13°N	8.24°W	195	IPMA	---

The weather stations in the Seia region were installed in March 2020. In Lousã it was only possible to install the equipment in October 2020, namely due to the pandemic restrictions. Additional unexpected issues with the power supply and communication systems caused further delays, hence full availability of data from the weather stations in Lousã started only in February 2021.

The station of Penhas Douradas is the historical reference for Serra da Estrela, as it stands nearly at 1400 m asl. The station of Trevim is located at the top of Serra da Lousã, at 1167 m asl, with excellent exposure to the flow. The station of Espinheiro also has very good exposure, but is installed slightly below 1000 m asl. The weather stations of Seia-Aero and Lousã-Aero are both located in the valley (or slightly above it in the latter), in the aerodromes of each city. The station of Candal is installed in a narrow valley with a north-west/southeast orientation.

The data from IPMA's surface weather stations is observed at default heights (wind at 10 m, temperature and relative humidity at 2 m), but in the portable weather stations all the variables are observed at 2 m. To make the wind speed observations comparable, the 2 m data was extrapolated to the 10 m level using a logarithmic profile with a conservative value (0.1). This study only considers hourly data.

3. Forecast verification

The forecast verification shown here uses data from the operational versions of the NWP models used at IPMA. The high-resolution forecasts are from the AROME model (Seity *et al.*, 2011; Termonia *et al.*, 2018), which is run at IPMA four times a day (00, 06, 12 and 18 UTC) with a forecast range of 48 hours. This is a convective-scale limited-area model and is run with a horizontal resolution of 2.5 km. The second set of forecasts is from the global IFS/ECMWF model, namely the high-resolution (ECMWF-HRES), with a horizontal resolution of 9 km. The data used in this study is from the 00 UTC run and it considers hourly short-term forecasts (H+6 to H+30). The results shown here are a broad view of the forecast skill, as it provides only a score for the whole period. The metrics used here are the root mean square error (RMSE) and the bias (BIAS). The meteorological variables are the 10 m wind speed and the 2 m temperature and relative humidity. For conciseness only results for the summer of 2021 are shown (Table 3).

Table 3 – Forecast verification in the Lousã/Seia region, in the summer of 2021.

Station name	2 m temperature				2 m relative humidity				10 m wind speed			
	ECMWF		AROME		ECMWF		AROME		ECMWF		AROME	
	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS
Penhas Douradas	2,14	-0,27	1,99	0,10	17,89	-1,08	11,91	-3,68	2,76	-1,71	2,00	-1,21
Trevim	3,45	-0,78	2,39	0,24	25,08	-1,48	14,29	0,97	1,76	-0,73	1,72	0,83
Candal	1,84	-0,30	1,70	-0,81	15,09	0,19	9,77	0,04	1,93	1,46	1,72	0,83
Lousã-Aero	1,91	-0,47	1,47	-0,33	11,46	-6,14	10,17	-5,93	1,20	0,73	0,94	0,26
Seia-Aero	3,07	2,08	2,73	1,59	14,11	-10,95	15,39	-8,98	1,38	0,83	1,29	0,59
Espinheiro	1,74	-0,25	2,05	0,41	12,19	-2,17	11,91	-3,68	1,23	-0,17	1,22	-0,36

The results show that the RMSE in these stations is larger than what is usually computed in low lying regions in mainland Portugal. The large errors in Seia-Aero, with a strong positive bias in temperature and large negative bias in relative humidity, is mainly due to the fact that in this location the cold-pool effect is very effective in the nighttime period. The highest errors in the 2m relative humidity are in the high slope (above 1000 m asl), which is likely due to the large variability of this variable. For the 10 m wind speed, while there is a negative bias in the locations at higher altitudes, in the valley stations the forecasts over-estimate the observed values. Finally, it should be stressed that these results are only valid for the stations and period in study.

4. Case studies

Since the spring of 2021 several events with large temperature inversions or downslope windstorms have been observed in the nighttime period. In the three events shown below, observed and short-term forecast data is shown only in the nighttime, which is defined as the period between 00 and 06 UTC.

4.1. Temperature inversion in August 2021

On August 5/6th, 2021, an event of strong temperature inversion enhanced by large scale subsidence was observed. Figure 2 shows the ECMWF-HRES analysis of the geopotential, temperature and wind at the 850 hPa, valid at 00 UTC, on August 6th. The Azores high extended a ridge towards the east-southeast, which lead to large-scale subsidence, dry and stable conditions in mainland Portugal. At the 850 hPa level the flow was moderate or strong from the west-northwest.

Figure 3 shows the cross-section of the wind (parallel) and relative humidity over Serra da Estrela, using the H+6 ECMWF-HRES forecast, valid at 06 UTC, on August 6th. This plot shows a strong gradient of relative humidity, over the orographic ridge and on the leeside of the mountain, associated with downward motion of very dry air. At the 860 hPa level, around the real altitude of Penhas Douradas, the relative humidity had values around 15-20%. At the same time, the vertical profile in Lousã-Aero (Figure 4) shows an inversion layer between 800 m and 2200 m asl, where the temperature increases around 5ºC and the humidity decreases around 75%. The downward motion is strongest between 1800 m and 2000 m asl, with vertical speeds around -0.8 m/s. Figure 5 shows the time series of the observed 2 m relative humidity. This suggests that the base of the "real" inversion should be located above and close to the height of Trevim (1167 m asl). Also, the difference between the observed relative humidity in Trevim and Penhas Douradas is larger than the difference of the corresponding forecasted relative humidity, which suggests a stronger inversion in this layer. In fact, at 06 UTC the temperature in Penhas Douradas was 6.4ºC higher than the one observed in Trevim (not shown), while the 2 m relative humidity were, respectively, 13% and 100%.

Figures 6 and 7 show that this event was very challenging for NWP models, even in the case of the high-resolution AROME. While in Penhas Douradas both models suggested dry air reaching the station, they over-estimated the 2 m relative humidity values by around 20%, with AROME in closer agreement with the observations. In Trevim, none of the models suggested the values of 20-30% during the nighttime on August 5th.

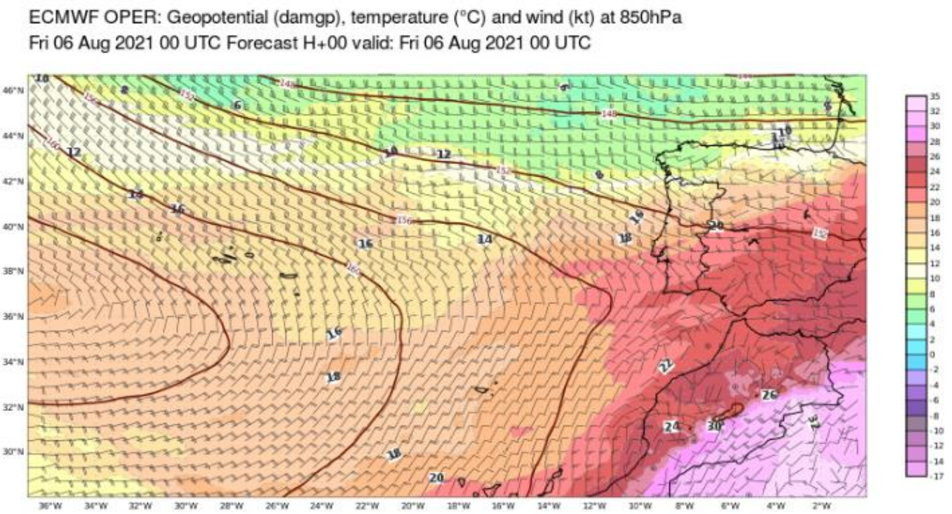

Figure 2 – ECMWF-HRES analysis of the geopotencial height, temperature and wind at the 850 hPa level, valid on August 6th, 2021, at 00 UTC.

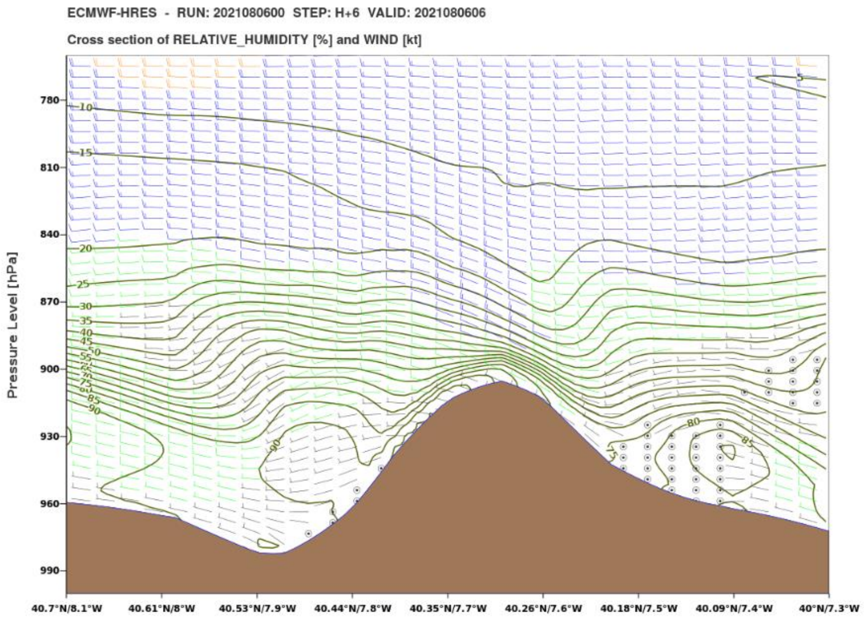

Figure 3 – Cross-section (orientation NW-SE) of relative humidity and wind (parallel) over Serra da Estrela, from a short-term ECMWF-HRES forecast, valid on August 6th, 2021, at 06 UTC.

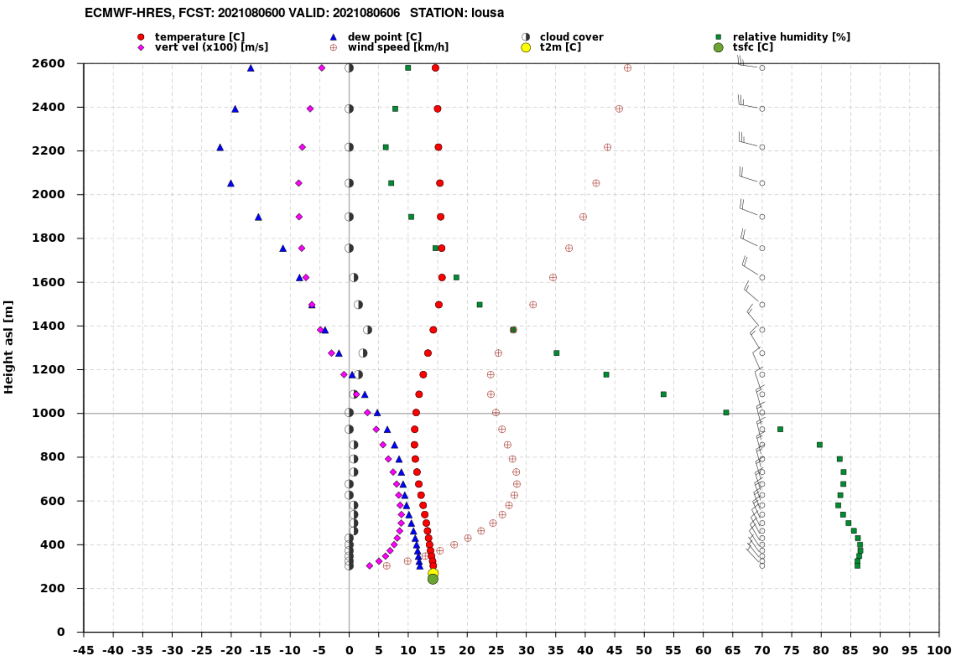

Figure 4 – ECMWF-HRES profile for Lousã-Aero, valid on August 6th, 2021, at 06 UTC.

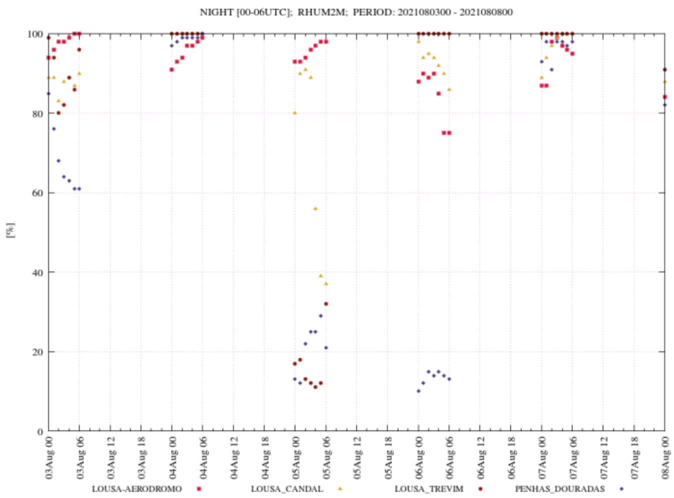

Figure 5 – Time series of the observed 2m relative humidity, in the weather stations located in the Lousã region and Penhas Douradas. Data in the period August 3rd – 8th, 2021.

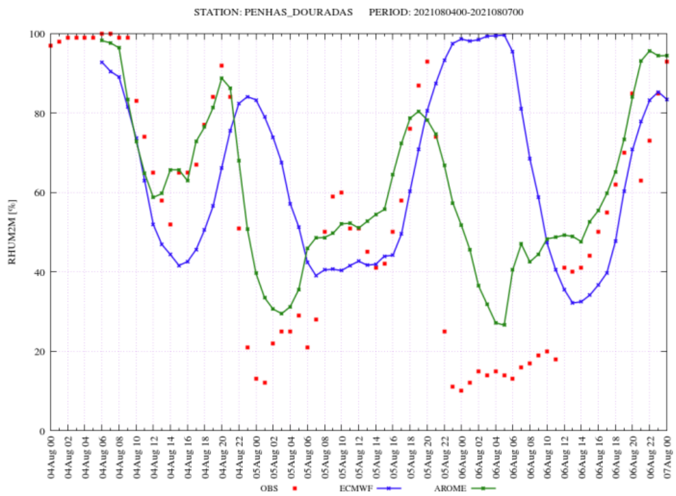

Figure 6 – Time series of observed and forecast (ECMWF-HRES and AROME) 2m relative humidity in Penhas Douradas, on August 4th – 7th, 2021.

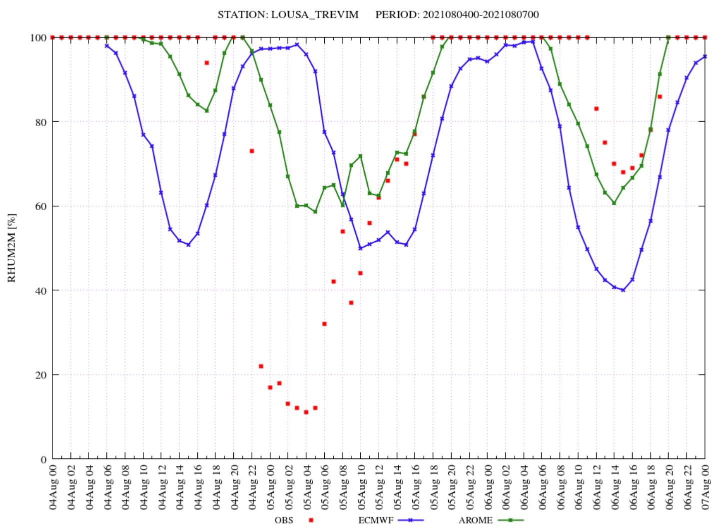

Figure 7 – Time series of observed and forecast (ECMWF-HRES and AROME) 2m relative humidity in Trevim, on August 4th – 7th, 2021.

4.2. Downslope windstorms

The two downslope windstorms briefly described in this paper were observed on March 31st, 2021, and March 28th, 2022. Figures 7a and 9a show the 00 UTC analysis of the geopotential, temperature and wind at the 850 hPa. Figures 7b and 9b show the cross section of the wind and relative humidity over Serra da Estrela, with a NW-SE orientation, using short-term ECMWF-HRES forecasts (H+6), valid at 06 UTC in each event. Figures 8 and 10 show the AROME forecasts of the 3 hour maximum 10 m wind gust and the 2 m temperature, valid at 03 UTC on each date.

In both events, a low pressure system was centred southwest of Iberia, close to Madeira, which originated a moderate or strong south-easterly flow. The cross sections show that the short-term ECMWF-HRES forecast was able to provide guidance into the strong downslope wind. In both cases, this model suggested much lighter wind speeds close to the valley. The AROME forecasts suggested south-east winds (not shown), with wind gusts in the 70-80 km/h range in the north-western slopes of the mountain range. The observed 2 m temperatures (not shown) were much higher than expected for the time of the year, mainly on the event in March 2022.

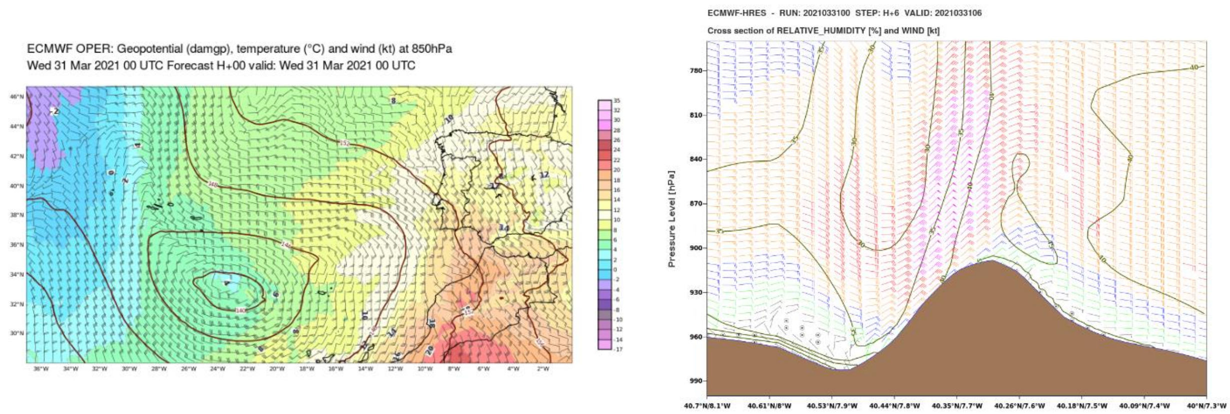

Figure 7 – ECMWF-HRES analysis of the geopotencial height, temperature and wind at the 850 hPa level, valid on March 31st, 2021, at 00 UTC (left). Cross-section (orientation NW-SE) over Serra da Estrela, from a short-term ECMWF-HRES forecast, valid on March 31st, 2021, at 06 UTC (right).

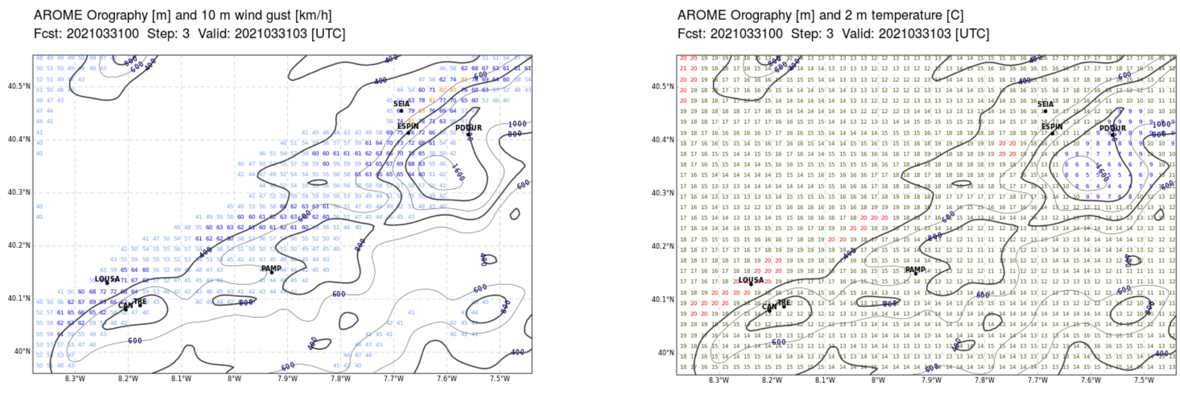

Figure 8 – AROME forecasts (H+3) of the 3 hour maximum 10 m wind gust (left) and 2 m temperature(right), valid on March 31st, 2021, at 03UTC.

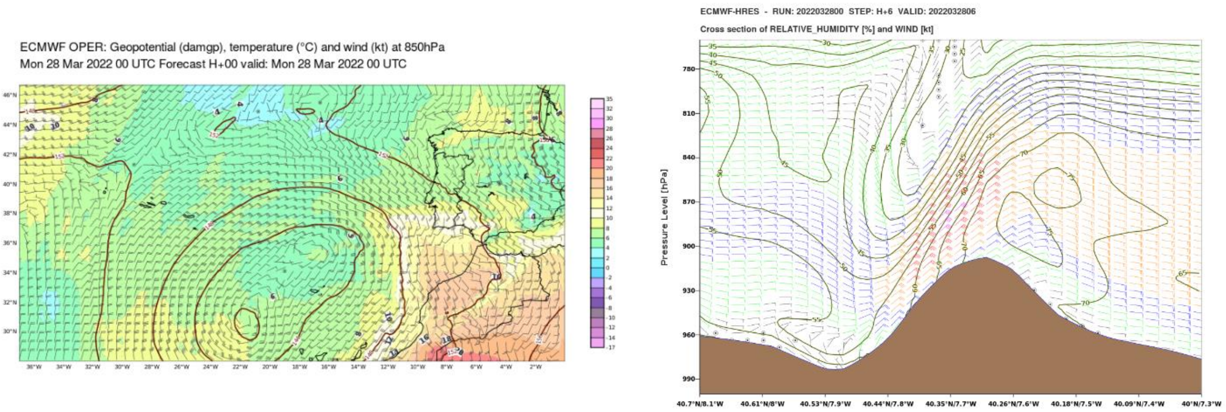

Figure 9 – (a) ECMWF-HRES analysis of the geopotencial height, temperature and wind at the 850 hPa level, valid on March 28th, 2022, at 00 UTC. (b) Cross-section (orientation NW-SE) over Serra da Estrela, from a short-term ECMWF-HRES forecast, valid on March 28th, 2022, at 06 UTC.

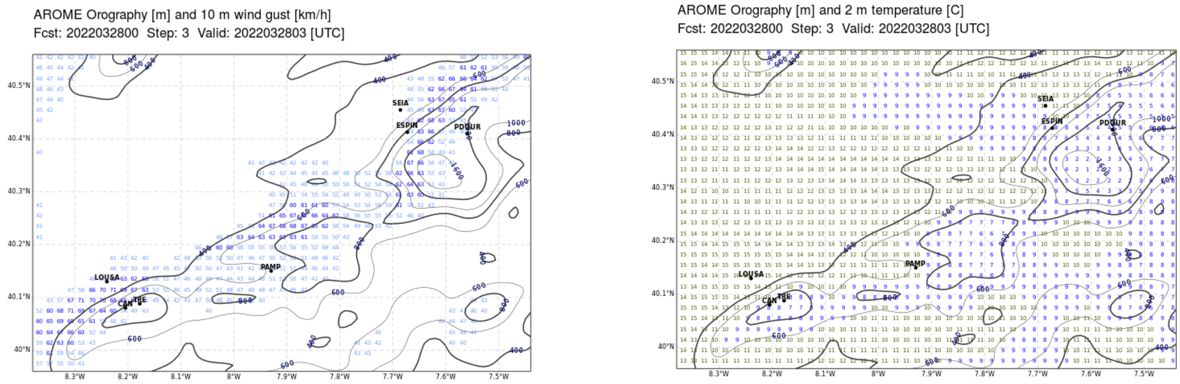

Figure 10 – AROME forecasts (H+3) of the 3 hour maximum 10 m wind gust (left) and 2 m temperature(right), valid on March 28th, 2022, at 03UTC.

The discussion above on downslope windstorms shows that ECMWF and AROME forecasts provide useful guidance in the broad features of these events, at least in the Lousã/Estrela mountain range. However, it must be stressed that these circulations are extremely challenging for NWP models (Haraldur *et al.*, 2021), as they are very sensitive to the initial conditions, namely the wind profile, atmospheric stability, direction of the flow into the mountain range and model horizontal resolution. Additionally, as turbulence plays a key role in these circulations, extreme caution is advisable if NWP direct model output is to be used operationally, as large differences between forecast and observations at specific locations are most likely to occur.

5. Final remarks

The results shown in this study highlight the challenges of weather forecasting in complex terrain. Even though NWP data provides useful guidance on the broad features of many events, comparing forecasts and observations clearly shows that large difference are very common. Therefore, these results show that extreme caution is advisable when direct model output of NWP data is used as a guidance for the weather data at a specific site.

6. Acknowledgments

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7. References

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