SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2017
Project Title:	EFFECT OF THE SURFACE HETEROGENEITIES IN THE ATMOSPHERIC BOUNDARY-LAYER
Computer Project Account:	SPESTURB
Principal Investigator(s):	Joan Cuxart and Maria A. Jiménez
Affiliation:	Universitat de les Illes Balears (UIB)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1st January 2015
Expected end date:	31st December 2017

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	150000	15000	150000	131500
Data storage capacity	(Gbytes)	200	200	200	100

Summary of project objectives

(10 lines max)

The current special project (2015-2017) is linked to the previous one (2012-2014) devoted to study the organization of the flow at lower levels in complex (topography) terrain regions. Now the attention is focused again in complex terrain regions but especially in areas with (surface) small-scale heterogeneities (related to temperature, soil moisture, vegetation or soil properties, among others). The aim of the project is to evaluate the impact of these small-scale heterogeneities in the spatial and temporal evolution of the atmospheric boundary layer, with special emphasis during the morning and evening transitions. The studied areas are the island of Mallorca and the Pyrenees, both taken as example of complex terrain regions with large surface heterogeneities.

Summary of problems encountered (if any)

(20 lines max)

Summary of results of the current year (from July of previous year to June of current year). This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

This project is the continuation of a former one devoted to the study of the stably stratified boundary layer (SPESTURB, 2002-2011) which gradually evolved into the study of the Atmospheric Boundary Layer (ABL; SPESTURB, 2012-2014) over complex terrain in weak general pressure gradients, allowing to inspect the effect of the terrain-induced flows over the ABL characteristics. The analysis of atmospheric motions in complex terrain is made by our group through the combined use of experimental data (very often from campaigns that we organize or where we participate with our own instrumentation) and numerical modelling. The principal source of computing time for the very high-resolution simulations has been the SPESTURB project at ECMWF with the MesoNH model (Lafore et al., 1998).

The complexity of the studied regions has increased over time. Mesoscale runs made via the SPESTURB project have been focused on studying the organization of the flow at lower levels in:
(i) the Duero river basin: Low-Level Jet (using LES, Cuxart and Jiménez, 2007), cold pool formation (Martínez et al., 2010).
(ii) the island of Mallorca: nocturnal flows (Cuxart et al., 2007; Martínez and Cuxart, 2007; Jiménez et al., 2008) and sea-breeze (Cuxart et al., 2014; Jiménez et al., 2016).
(iii) the Ebro river basin: fog formation (Cuxart and Jiménez, 2012), mesoscale simulations and remote sensing (Cuxart et al., 2012), surface energy balance (Cuxart et al., 2015).
(iv) the Pyrenees: characterization of the downslope winds (Jiménez and Cuxart, 2014), description of the flow in a narrow valley N-S oriented (Jiménez et al., 2017, in preparation), the temperature heterogeneities a different spatial scales (Cuxart et al., 2016) or the evaluation of the anisotropy during the afternoon and evening transitions (Lampert et al., 2016).

From the beginning of this project, we have concentrated our efforts in: **(i)** the Sea Breeze (SB) and Land Breeze (LB) in the island of Mallorca, **(ii)** the organization of the flow in La Cerdanya, an E-W oriented valley in the central Pyrenees about 20km long and 2km wide and **(iii)** further exploring the downslope winds during the BLLAST experimental field campaign (works initiated in the former special project). Preliminary results are summarized in the following sections.

1) The sea and land breeze in Mallorca (MSB14 experimental field campaign).

During September 2013 the Mallorca Sea Breeze (**MSB13**) experimental field campaign took place in the Campos basin (at the south of the Island of Mallorca, Western Mediterranean Sea, Figure 1). A morning transition case (from land to sea breezes) was sampled with a multicopter and a tethered balloon. A mesoscale simulation was done of this case with a setup similar to Cuxart et al. (2007). 2 nested domains were taken at 5km and 1km horizontal resolutions and 3m in the vertical (gradually stretched). The observed features during the phases in the morning transition (according to Cuxart et al. 2014) are compared to the model outputs and results are further explained in Jiménez et al. (2016a). It was found that **the model was able to reproduce the turning of the wind from the land-breeze towards the sea-breeze directions as well as the thermal structure in the lower atmosphere**. However, the model was not able to reproduce the nocturnal cold pool, resulting in an unrealistic evolution of the temperature at lower levels during the previous phase. Nevertheless, at the end of this phase the model is reproducing the observed patterns as well as the evolution of the following phases (preparatory and development) during the morning transition. This wrong temporal evolution of the model during the previous phase might be related to a **wrong representation of the surface properties**.

A year later (from 26th May to 6th June 2014) the **MSB14** experimental field campaign took place at the same site. Continuous measurements in Ses Covetes (red cross in Figure 1b) were taken from a surface weather station (high-frequency sampling sensors, sonic), a multicopter and a tethered balloon during the 5 IOPs (see description in Figure 2). Due to the strength of the turbulence in the mature phase of the SB, only vertical soundings were sampled during the night-time and the morning and evening transitions (Figure 2). In order to further understand the observations, a high-resolution mesoscale simulation was done with a similar setup used for the MSB13 case: 2 nested domains (at 5 km and 1km resolutions). Besides, a third domain was taken, centered in the Campos basin at 250 x 250 m resolution (see Figure 1b).

The modelled organization of the flow at lower levels for IOP3 is shown in Figure 3. It is found that during night-time the air flows out of the island due to the **combined effect of the LB and downslope winds** and a similar interaction happens during the day (SB interacts with upslope winds). Although all model domains behave similarly, the organization of the flow is more realistic at 250m resolution where the topography is better reproduced.

To verify the model results they are compared to the multicopter and tethered balloon temperatures sampled in Ses Covetes (Figure 4). It is found that the model is able to reproduce the thermal structure during the morning and evening transitions. However, it fails to reproduce the strong surface cooling during night-time (as previously described in Jiménez et al., 2016 for the MSB13 studied case). The modelled surface temperature gradient between land and sea is similar to the one reported from satellite (MODIS and Meteosat) indicating that the model is **able to capture this temperature difference** (Figures 5 and 6), one of the main process to start and maintain the sea-breeze. Comparing the model outputs to other sites in the Campos basin (Ses Salines, 1km inland and Porreres, 15km inland) it is seen that the model, especially the inner domain (D3, at 250m resolution) is closer to observations (Figure 4).

It is important to mention the limitations to verify the model outputs in coastal and mountain regions. Terrain and soil uses, among others, change drastically and this variability is not included in the surface databases that models typically use. This fact can explain the differences between the model and single-point observations or satellite-derived products. These results are under discussion and a manuscript is in preparation.

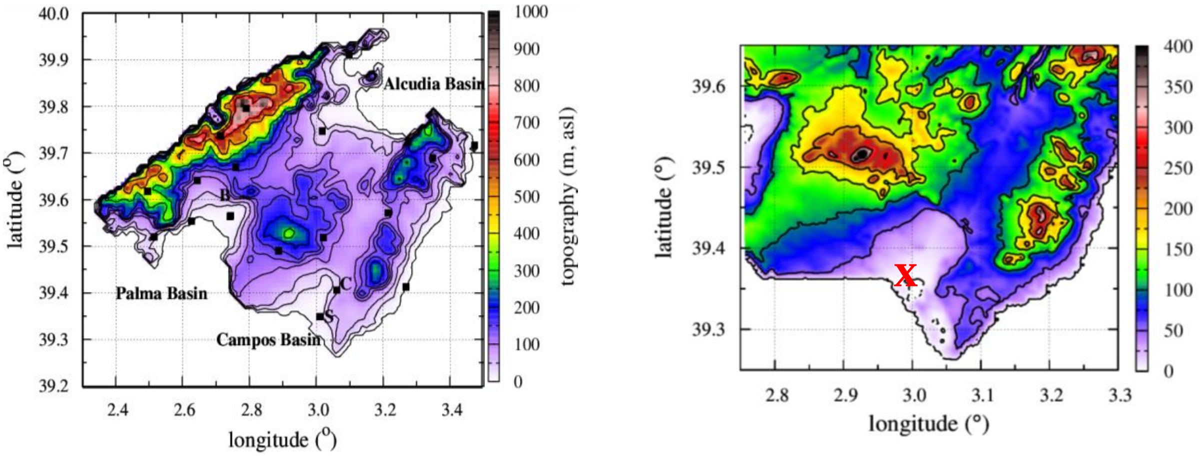
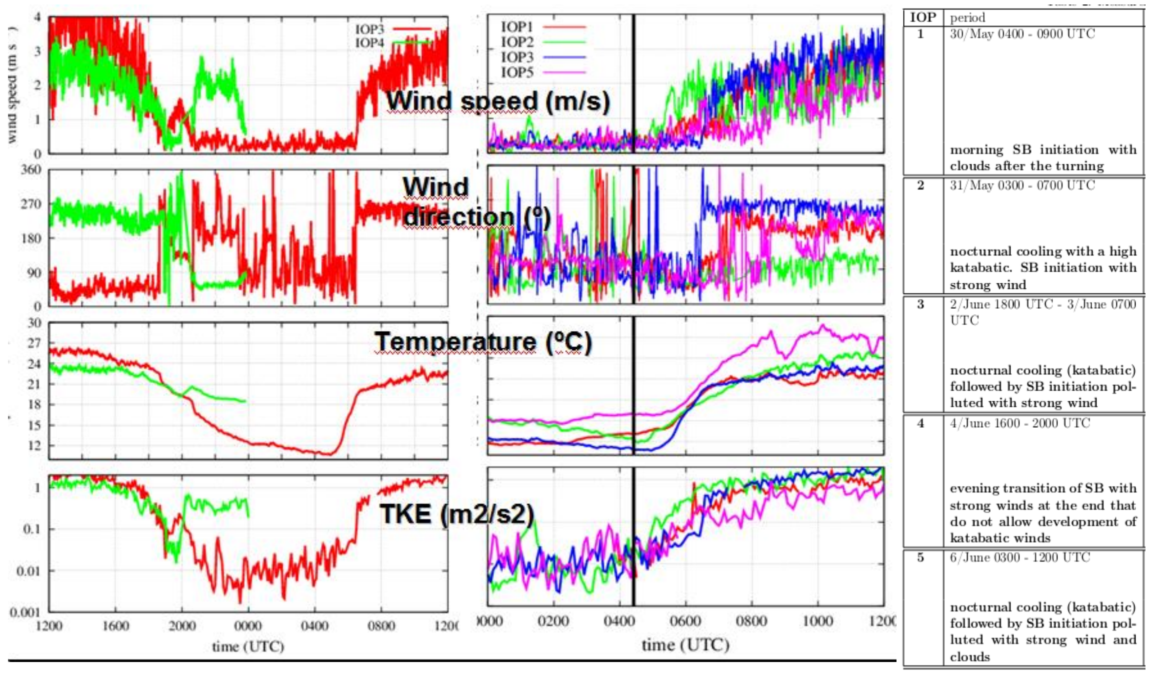


Figure 1. Topography of (a) the second domain (at 1km resolution) of the run and (b) the third nested domain at 250m resolution. The location of the main site during MSB14 (Ses Covetes) is indicated with a red cross and in dots the surface weather stations from AEMET used to verify the model outputs.



IOP	period
1	30/May 0400 - 0900 UTC morning SB initiation with clouds after the turning
2	31/May 0300 - 0700 UTC nocturnal cooling with a high katabatic. SB initiation with strong wind
3	2/June 1800 UTC - 3/June 0700 UTC nocturnal cooling (katabatic) followed by SB initiation polluted with strong wind
4	4/June 1600 - 2000 UTC evening transition of SB with strong winds at the end that do not allow development of katabatic winds
5	6/June 0300 - 1200 UTC nocturnal cooling (katabatic) followed by SB initiation polluted with strong wind and clouds

Figure 2. Observations in Ses Covetes during the 5 IOPs of the MSB14 experiment.

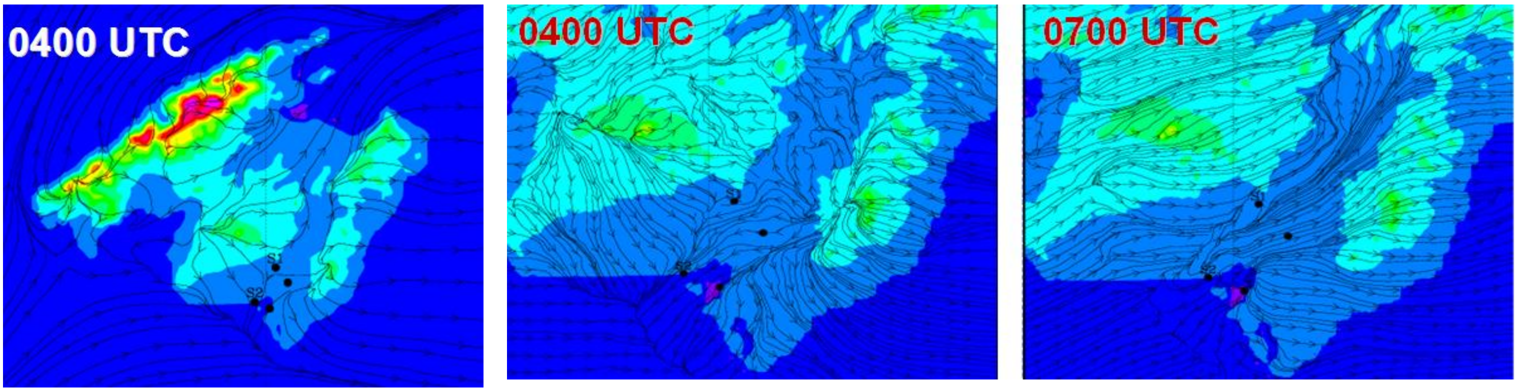
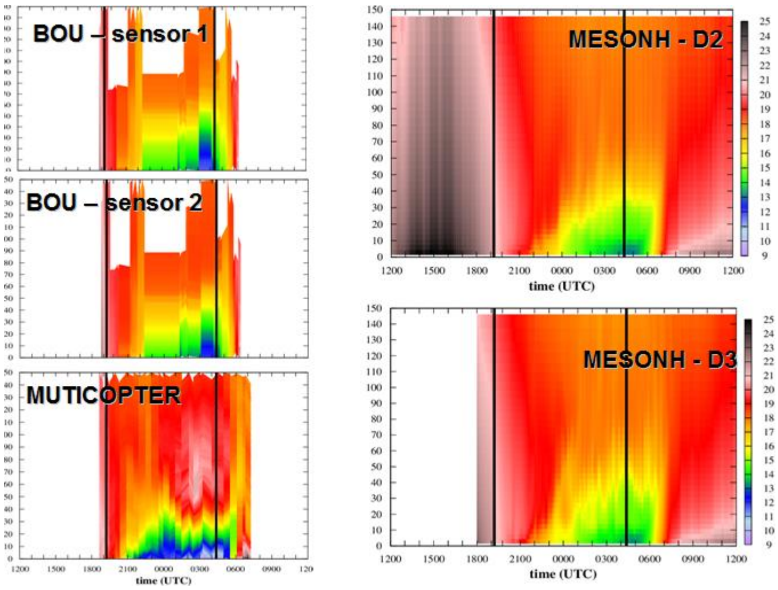


Figure 3. Streamlines at 10m (agl) over the topography (in colours) during IOP 3 (3rd June 2014) at 0400 UTC and at 0700 UTC, for the land and preparatory phases of the diurnal cycle of the SB, respectively.



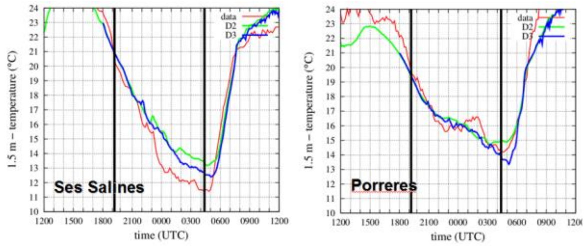


Figure 4.
(LEFT) Observed and simulated time series of the vertical profiles for temperature.
(TOP) Modelled and observed time series of the 2m temperature at two different locations in the Campos basin.

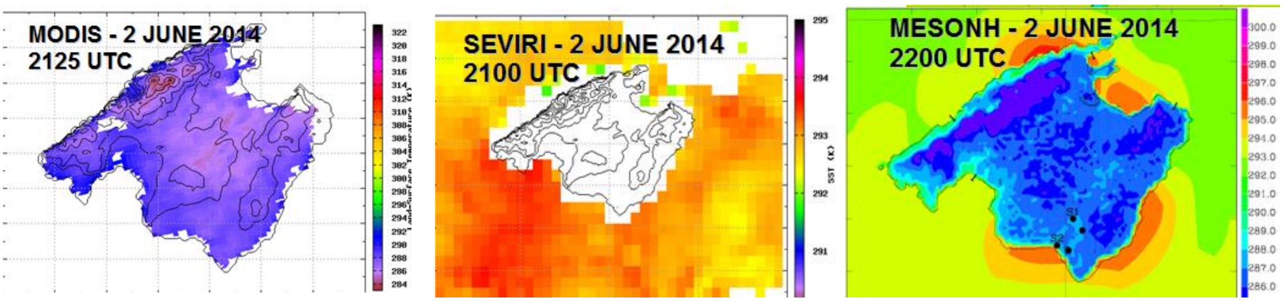


Figure 5. Satellite-derived surface temperatures compared to those obtained from the model during the evening transition sampled during IOP 3.

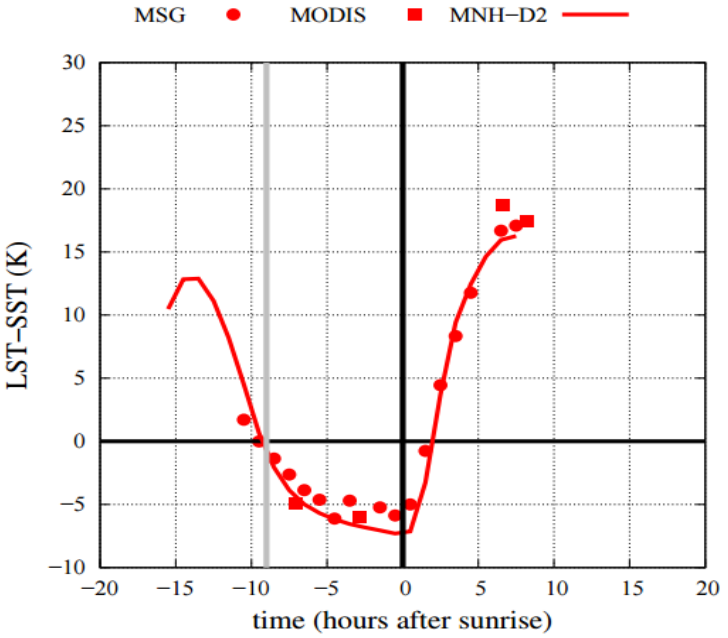


Figure 6. Modelled and satellite derived surface temperature differences between land and sea for IOP 3. The temperatures are averaged over a similar area covering: the center of the Campos basin (LST) and the bay over the sea in front of the Campos basin (SST). Time is shifted to the sunrise hour (black vertical line) and sunset is indicated with a grey line.

2) Organization of the flow at lower levels in a complex terrain valley in the central Pyrenees (La Cerdanya)

La Cerdanya is a valley located in the central Pyrenees 30 km long and 9 km wide oriented to the NE to SW directions. It is taken in this study as an example of **complex terrain valley, in terms of topography but it is also covered by heterogeneous surfaces** (forest, no vegetation, snow, …). In order to further understand the organization of the flow at lower levels, a representative case (based on the climatology of the surface weather stations of the region, Conangla et al., 2017) during fall (snow still not present at the mountains top) with a clear diurnal cycle is taken (weak pressure gradient conditions and clear-skies). A period of 48 hours, starting on September 30th 2011 is simulated with the MesoNH model with two nested domains at 2 x 2 km and 400 x 400 m resolution (see Figure 6).

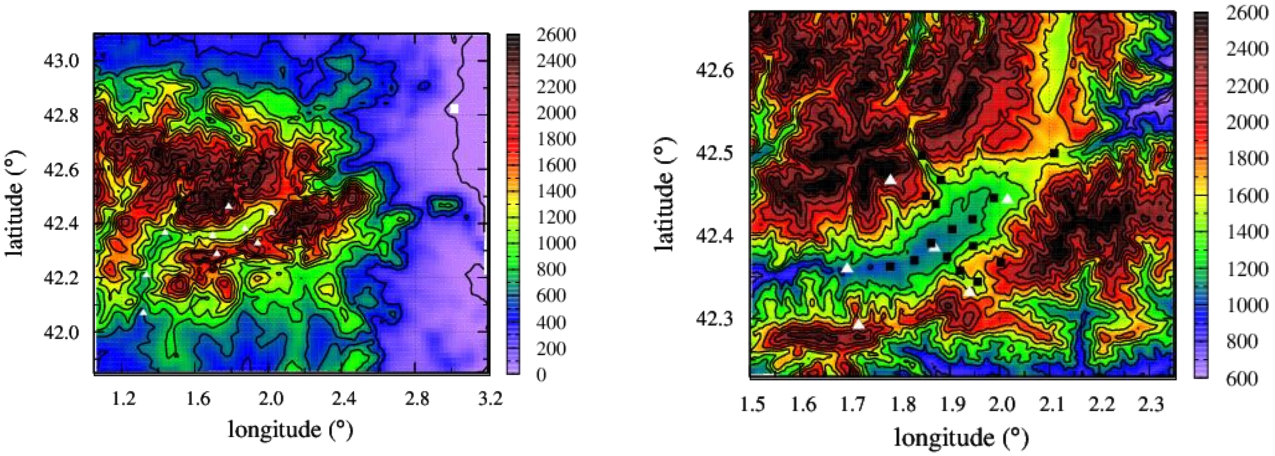


Figure 6. Topography of the two nested domains at (LEFT) 2 x 2 km and (RIGHT) 400 x 400 m resolution, respectively. The locations of the AEMET and MeteoFrance automatic weather stations are indicated in white triangles and some interesting points that we are further exploring are in black dots.

It is found that **during night-time downslope and down-valley** winds are generated and the temporal evolution of them in La Cerdanya valley strongly depends on the slope winds generated in the tributary valleys at the north and south (Figure 7, left). An opposite behaviour is found during day time (Figure 7, right). Upslope winds are present in the northern mountains of La Cerdanya whereas those at the south are strongly influenced by the strong upslope winds generated at the south side, outside La Cerdanya. Model results are verified with satellite observations (MODIS, land-surface temperature, Figure 8) and the surface weather observations (Figure 9). It is found that **the model is able to reproduce the main observed surface temperature patterns as well as the cold pool** in the lower part of the valley (Figure 9), close to the exit (Das, labelled as DP in Figure 7). Modelled 1.5m temperatures are better reproduced in the upper valley (Figure 9, indicated as LEO in Figure 7). The model tends to overestimate the wind speed although it is capturing the turning of the wind. Further results are found in Conangla et al. (2017) where the cold pool evolution is explored through model and satellite-derived temperatures.

Now the efforts are concentrated to better understand the cold pool formation close to Das (the coldest area of the valley during night-time), a place that the climatological analysis shows the prevalence of this nocturnal process. During October 2015 an experimental field campaign was conducted to better characterize experimentally the cold pool formation close to Das (Cerdanya Cold Pool experiment 2015, **CCP15**). 4 IOPs are taken to analyse the cold pool formation through mesoscale simulations (setup similar to the previous one) and observations. Preliminary results are shown in Figures 10 and 11 where model outputs are validated through observations (WindRass and surface energy budget station, respectively). This work is still in progress.

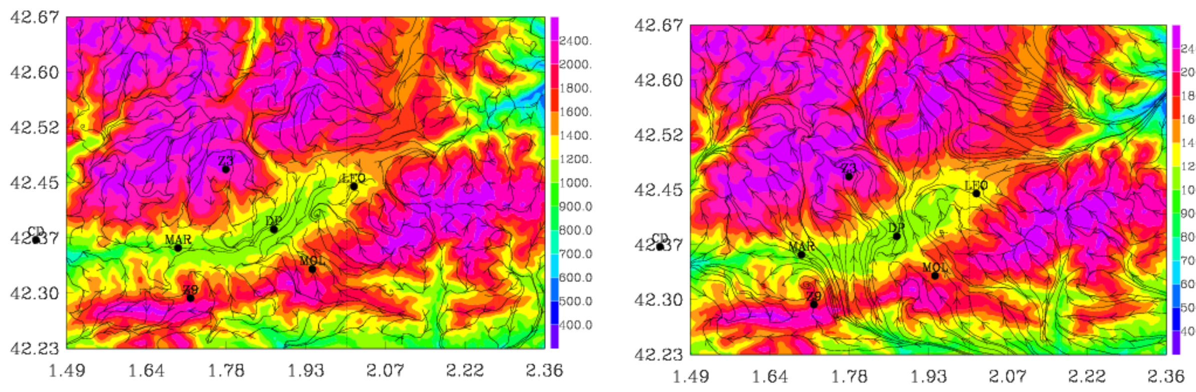


Figure 7. Streamlines at 25m (agl) together with the topography obtained from the inner domain on 1st October 2011 at (LEFT) 0200 UTC and (RIGHT) 1300 UTC.

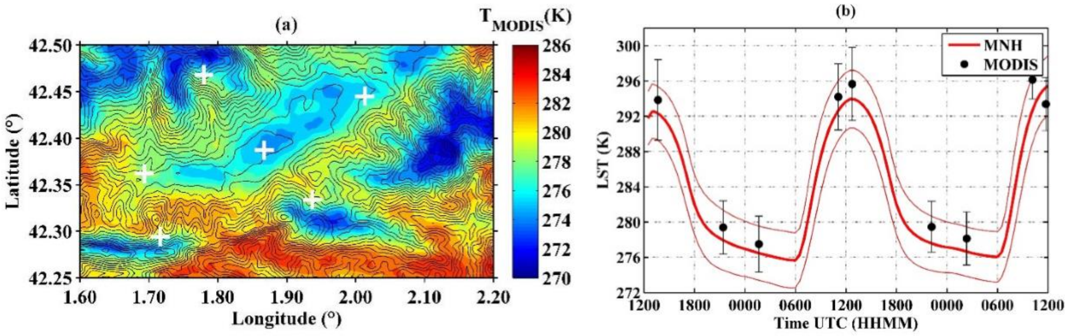


Figure 8. (a) Land Surface Temperature in a zoom inside the domain 2 derived from MODIS satellite at 2/October/2011 0220 UTC. Crosses show the AWSs location. (b) Evolution, from 30/09/2011 1200 UTC to 02/10/2011 1200 UTC, of the average surface temperature of the entire domain 2, obtained by the MesoNH model each 30 minutes (with his standard deviation), compared with the values obtained from the available nine images of MODIS satellite.

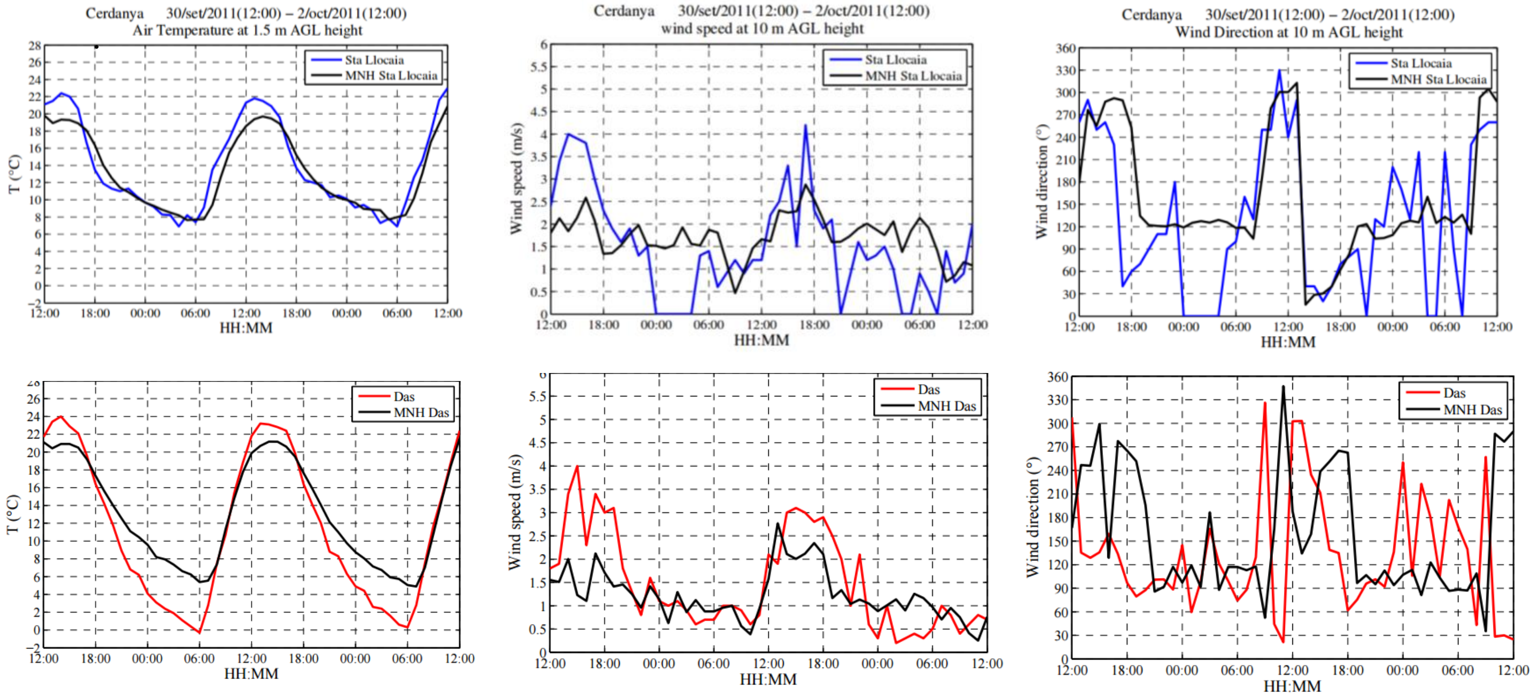


Figure 9. Modelled and observed time series (TOP) in the upper valley and (BOTTOM) in the lower valley, close to the narrow exit. These sites are indicated with LEO and DP in Figure 7, respectively.

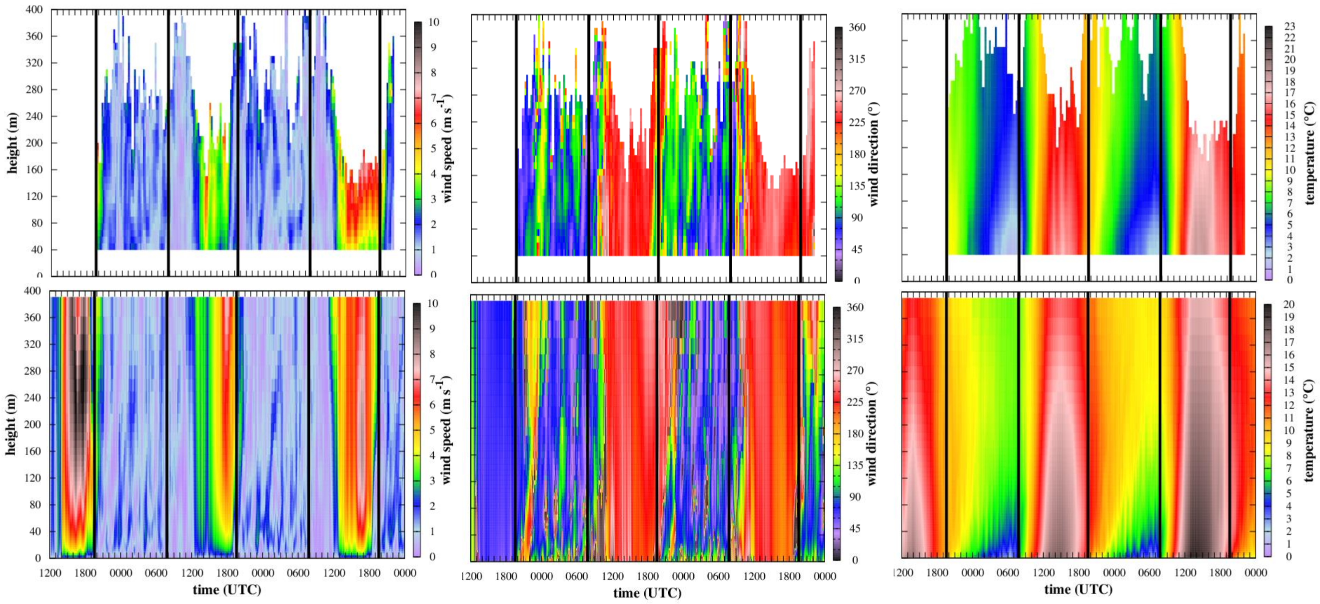
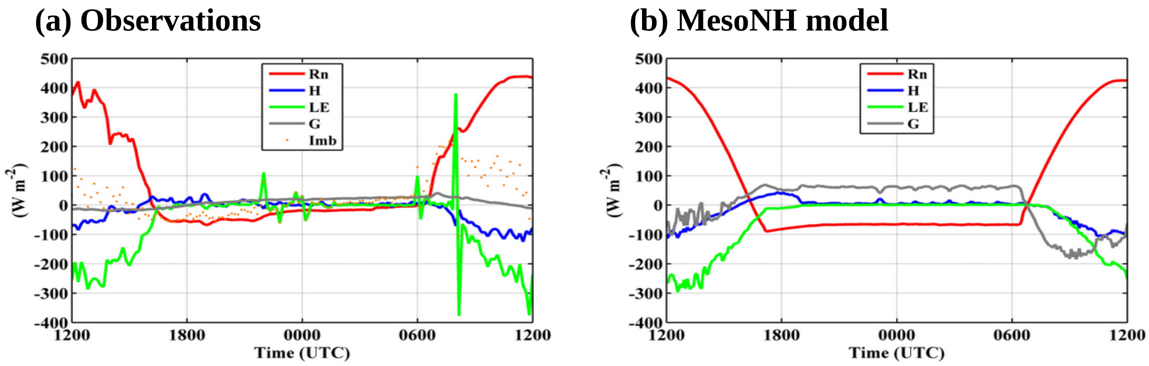


Figure 10. Time series observed by the WindRass in Das (top) together with the modelled ones (bottom) for wind and temperature during IOPs 2, 3 and 4 during CCP15 (9-11 October 2015).


(a) Observations

(b) MesoNH model

Figure 11. Time series observed and simulated surface energy balance for IOP 3 during CCP15 (10-11 October 2015).

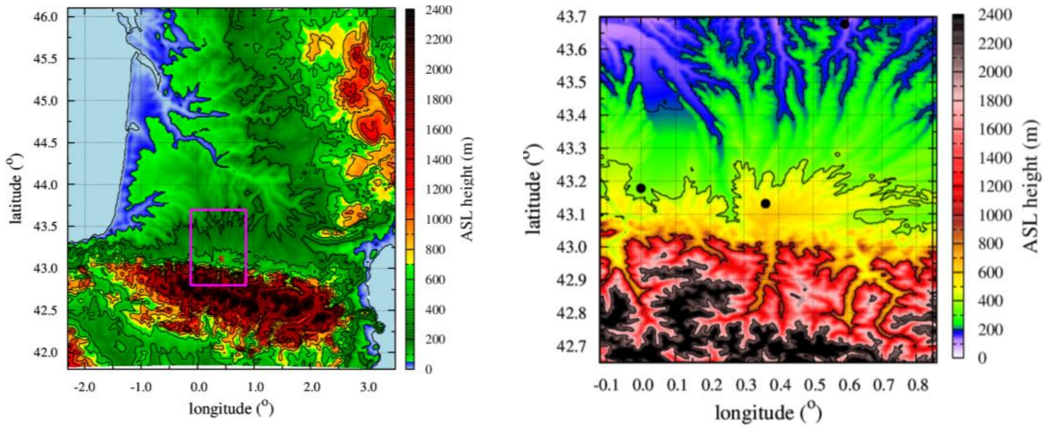
During winter 2017, another experimental field campaign was conducted at this site (**CCP17**) to sample the cold pool when snow is present in the valley. The valley was more densely sampled than during CCP15 where apart from WindRass, surface energy balance station, captive balloon and multicopter, a network of observations was installed in the cold pool region to properly capture the spatial variability of the cold pool. The analysis of the observations of the 10 IOPs is under work and the first run is just finished. It consists on a 6 day period at the end of 2016 when a strong cold pool event was sampled, lasting for several days with no snow in the bottom of the valley but with temperatures much lower than the previous studied IOPs of CCP15.

3) Downslope winds during the BLLAST experimental field campaign

The Boundary-Layer Late Afternoon and Sunset Turbulence (**BLLAST**) field campaign was conducted from 14 June to 8 July 2011 in southern France, in an area of complex and heterogeneous terrain. The main objective of BLLAST was to characterize the physical processes that take place during the afternoon and evening transitions (Lothon et al., 2014). Measurements were taken at Lannemezan (Figure 12), placed over a plateau at 600 m above sea level (a.s.l.). It is approximately 20 km north of the Pyrenees mountain range and at the exit of the Aure valley (a narrow valley, 30 km long, with the main axis oriented approximately in the north–south direction.

In the previous special project (2012-2015) mesoscale simulations were performed for the case of 1-2 July 2011 (corresponding to IOP9) to better characterize the nocturnal flow in Lannemezan. In the current special project, a total of **6 IOPs have been simulated**. They correspond to IOPs where **clear-sky and weak pressure gradient conditions** were present (see details in Table 1). Two nested domains are taken (see Figure 12) and the setup is similar to the previously simulated case 1 year before the BLLAST campaign (Jiménez and Cuxart 2014).

The aim of the current work is to better describe the **dynamics of the Aure valley**, since there are not available observations. Furthermore, the model results will be useful to describe the main features of the nocturnal exit valley jet and the ambient conditions that favour its formations. This jet is typically generated due to the accumulation of downslope and down-valley winds at the exit of a valley, as it is described in Whiteman (2001).


(a) Domain 1
(2km x 2km resolution)

(b) Domain 2
(400m x 400m resolution)

Figure 12. Topography of the 2 nested domains of the simulation of the IOPs (clear sky and weak pressure gradient conditions) during the BLLAST field campaign: The location of Lannemezan is indicated with a symbol.

IOP	Period	wind direction(*) 1300 UTC	wind direction(*) 2300 UTC	sky	Large-scale circulation(**)
1	15-16 June	N	-	clouds and rain	weak winds, not clear direction
2	19-20 June	N	low S	clear skies,light rain	high-pressure, weak E wind
3	**20-21 June**	E	low S	clear skies	high-pressure, weak NE-E wind
4	24-25 June	-	E/S	clouds only during day	Atlantic high-pressure, strong NE-E winds
5	**25-26 June**	E	E/S	clear skies	Atlantic high-pressure, strong NE-E winds
6	**26-27 June**	E	E/S	clear skies	Atlantic high-pressure, winds from N-E
7	27-28 June	-	-	clouds	strong E winds
8	30-1 July	-	-	clouds and rain	strong N winds (fronts)
9	**1-2 July**	N	E/S	clear skies	Atlantic high-pressure, weak NE winds
10	**2-3 July**	N	E/S	clear skies followed by clouds	Atlantic high-pressure, weak NE winds
11	**5-6 July**	N	W	clear skies	Atlantic high-pressure, weak S winds

(*) extracted from the soundings within the BL extend (about 1000 m agl). Slope wind directions in Lannemezan: upslope (N) and downslope (S).
(**) corresponding to the surface level. At higher levels winds were from W for all the IOPs.
(-) indicates no sounding.

Table 1. Description of the different IOPs during the BLLAST experimental field campaign and in bold those studied in depth with mesoscale modelling.

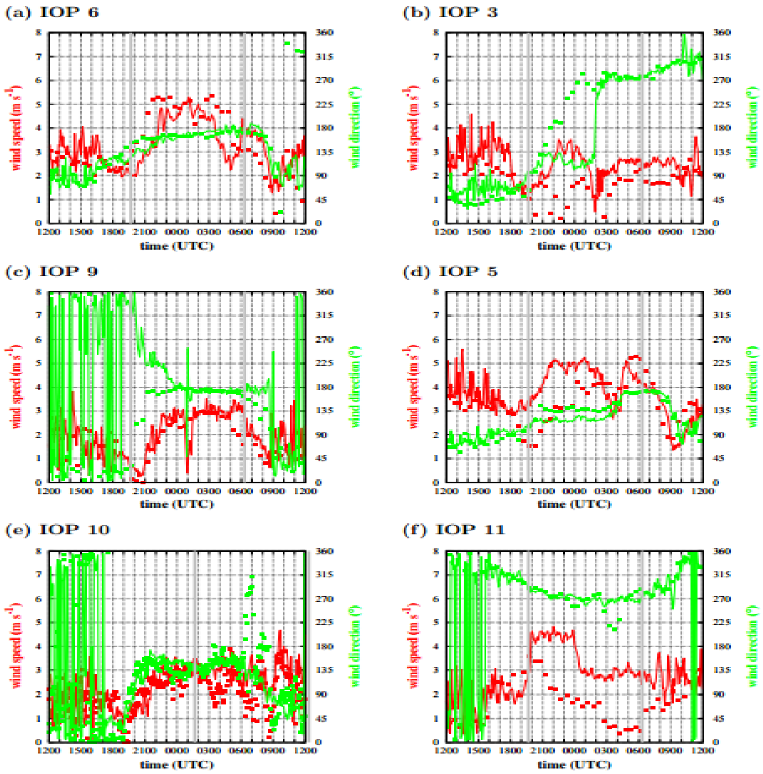
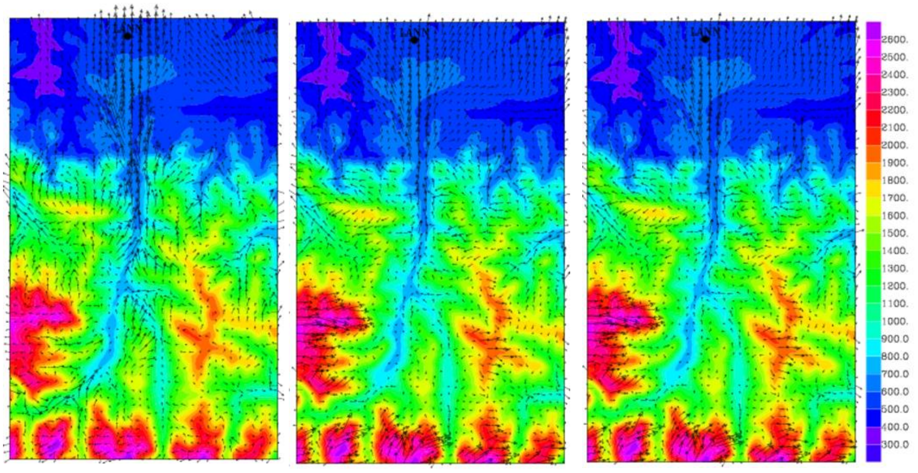


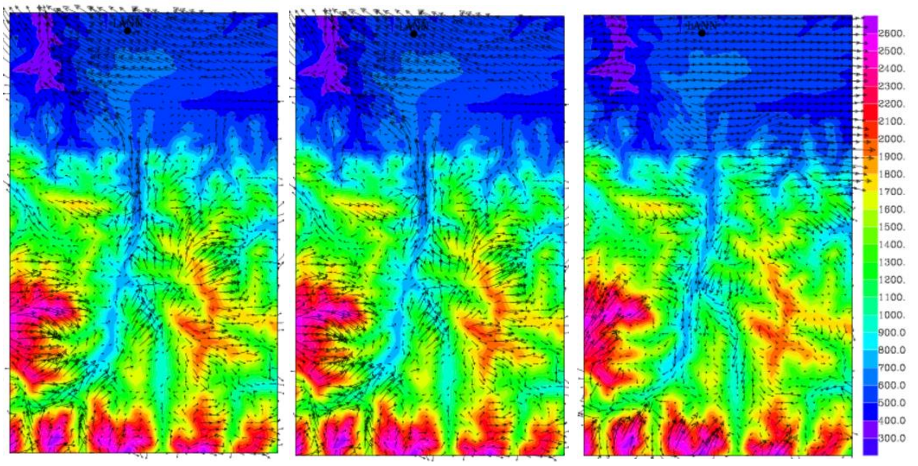
Figure 13. Verification of the runs for the different IOPs during BLLAST for the modelled and observed wind at 15 m AGL. Further details of the IOPs in Table 1. On the (LEFT) the IOPs were southerly winds were reported in Lannemezan (corresponding to the downslope direction) and on the (RIGHT) cases when winds in Lannemezan were not from south during most of the night.

IOP 6 IOP 9 IOP 10



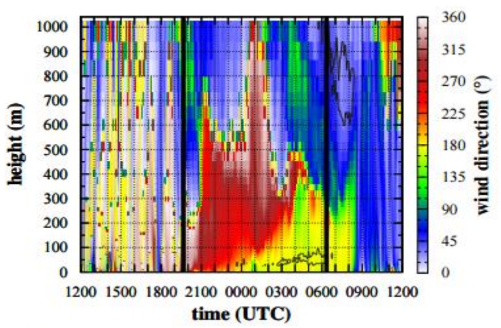
CASES WITH
DOWNSLOPE WINDS

IOP 3 IOP 5 IOP 11

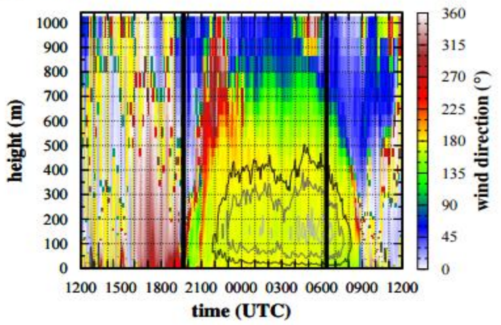


OTHER CASES

Figure 14. Wind vectors at 50m AGL and topography (in colours) for an area covering the Aure valley and the plateau where Lannemezan is placed. At the TOP the IOPs with nocturnal downslope circulations and at the bottom other cases.



(a) Lannemezan



(b) Exit Valley Jet

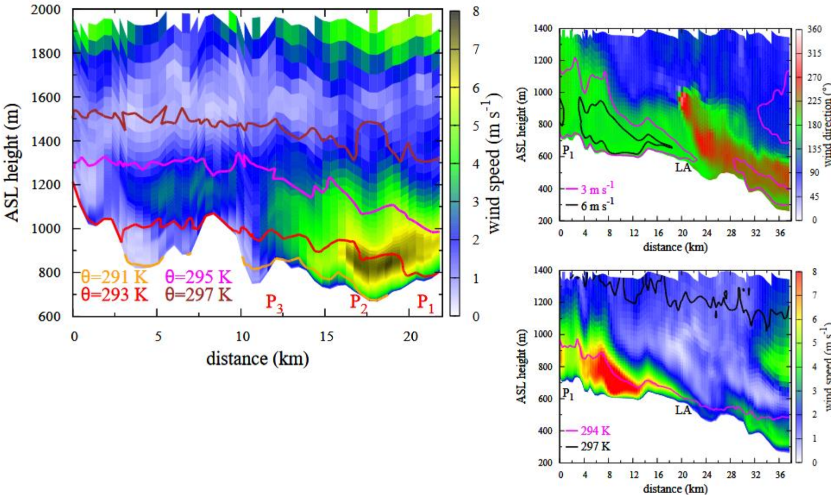


Figure 16. Vertical cross-sections along the Aure valley (top) and from the exit of the Aura valley towards the foothills at 0400 UTC for IOP 9.

Figure 15. Temporal evolution of the vertical profiles of the wind direction (in colours) and speed (in grey-scale lines, black 4m/s) for IOP 9 in (a) Lannemezan and (b) at the exit of the Aure valley.

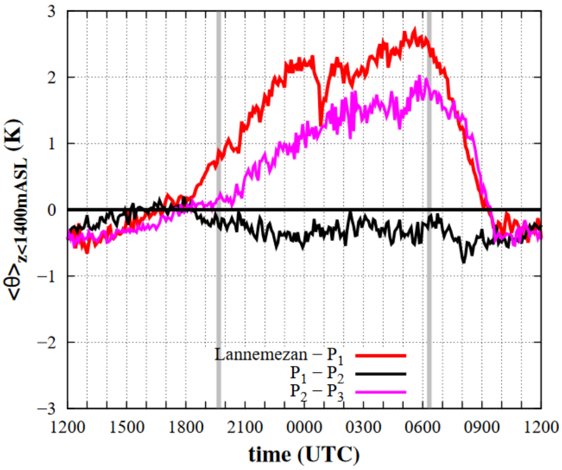


Figure 17. Time series of the differences between consecutive points (see their locations in Figure 16) of the vertically-averaged potential temperature (from the ground up to 1400 m ASL) for IOP 9.

Model results are validated with observations in Lannemezan since there are no available observations inside the Aure valley. For all simulated IOPs the model is able to reproduce the wind speed and direction in Lannemezan (Figure 13) as well as the temperature patterns (not shown). During the night-time, most of the IOPs present southerly winds in Lannemezan (corresponding to the downslope wind direction). However, for **IOPs 3 and 11 the large-scale winds did not allow the development of these slope circulations** and the wind direction during the night was from SE (veering to W) and W, respectively. Particularly, for IOP 5 wind direction was mainly from E during most of the night but it veered to S at about 0300 UTC, when the strong easterly wind weakened (Figure 14). The rest of simulated IOPs (6, 9 and 10) behave similarly and **downslope winds were present during the whole night** (southerly wind direction, Figure 14), in agreement with observations.

From the analysis of the model results it is found that an **exit valley jet** is generated in the Aure valley during night-time for the studied cases (see for instance Figure 16), except for IOP 11 (see details in Table 1). Its main features depend on the ambient conditions such as the wind speed and direction of the synoptical or mesoscale winds at the foothills of the Pyrenees. The exit valley jet reaches Lannemezan (Figure 16) if large-scale winds at the foothills are weak or if they are moderate or strong when they diminish. Model results show that the exit valley jet weakens and lower when it travels from the exit of the valley towards the foothills, where Lannemezan is placed; interacting with the locally-generated flow at these sites (Figures 15 and 16). The model outputs are further analysed to better understand the physical mechanisms involved in the exit jet formation. It is found that downslope winds are generated at the mountain slopes close to sunset. They converge to the central part of the bottom of the valley and the exit jet is generated about 2-3 hours afterwards due to the accumulation of air in the narrow pass close to the exit of the valley. As it is seen in Figure 17, the thermal gradient between the exit of the valley and the plain enhances the propagation of the jet through the foothills.

IOP 10 is further analysed (Lampert et al., 2016) because the turbulence properties of the lower atmosphere (up to 300 m above ground level) were sampled with the **Meteorological Mini Aerial Vehicle (M^{2}AV)** from turbulently mixed to stably stratified atmospheric conditions. IOP 10 is similar to the previously described IOP 9. However for IOP 10 a **low-level jet was formed during the evening transition due to the interaction between the large-scale winds and the locally-generated downslope winds** (Figure 13b). It is found that during the AET the **anisotropy** of the turbulent eddies increases as the vertical motions are damped due to the stably stratified conditions (Figure 18a) and this effect is enhanced by the formation of a low-level jet after sunset (Figure 18b).

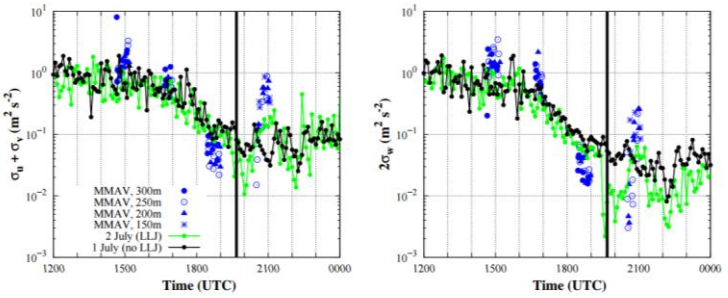


Figure 18b. The same as a but for the (LEFT) horizontal $\sigma_u + \sigma_v$ and (RIGHT) vertical $2\sigma_w$ variances computed from the tower observations at 60 m AGL during IOP 9 (without an LLJ, black line) and IOP 10 (with an LLJ, green line), together with those derived from M^{2}AV observations

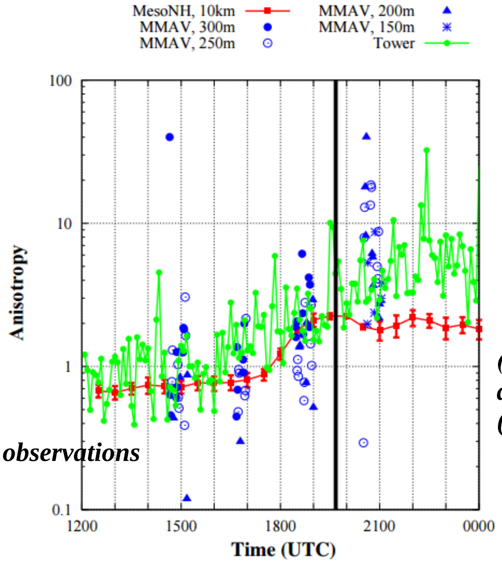


Figure 18a. Time series of the anisotropy computed from different sources: (1) M^{2}AV flight observations at 150, 200, 250 and 300 m a.g.l. during the four flights, each symbol representing a particular height (in blue); (2) tower measurements at 60 m a.g.l. every 5 min covering the afternoon–evening transition (in green); (3) model results averaged between 150 and 300 m a.g.l. to be close to the altitudes of the M^{2}AV observations considering a spatial area of 10 km × 10 km centred at Lannemezan (in red). The time of sunset is represented by a black vertical line. Note the logarithmic scale on the y axis. For M^{2}AV, $\sigma^2_u = \sigma^2_v$ is assumed.

List of publications/reports from the project with complete references

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J. Cuxart; L. Conangla; M. A. Jiménez, **2015**: Evaluation of the Surface Energy Budget equation with experimental data and the ECMWF model in the Ebro valley. *Journal of Geophysical Research-Atmospheres*. 120, pp. 1008 - 1022.

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Summary of plans for the continuation of the project

(10 lines max)

It is expected that during the second semester of 2017 we will continue exploring the mesoscale simulations already made (especially those related to CCP15 and CCP17). They are based on observations and further work is needed to complete the analysis and to understand the most relevant physical processes that take place in these complex areas. The current special project will finish by the end of 2017 and a proposal of the new special project for the next 3 years is already submitted.